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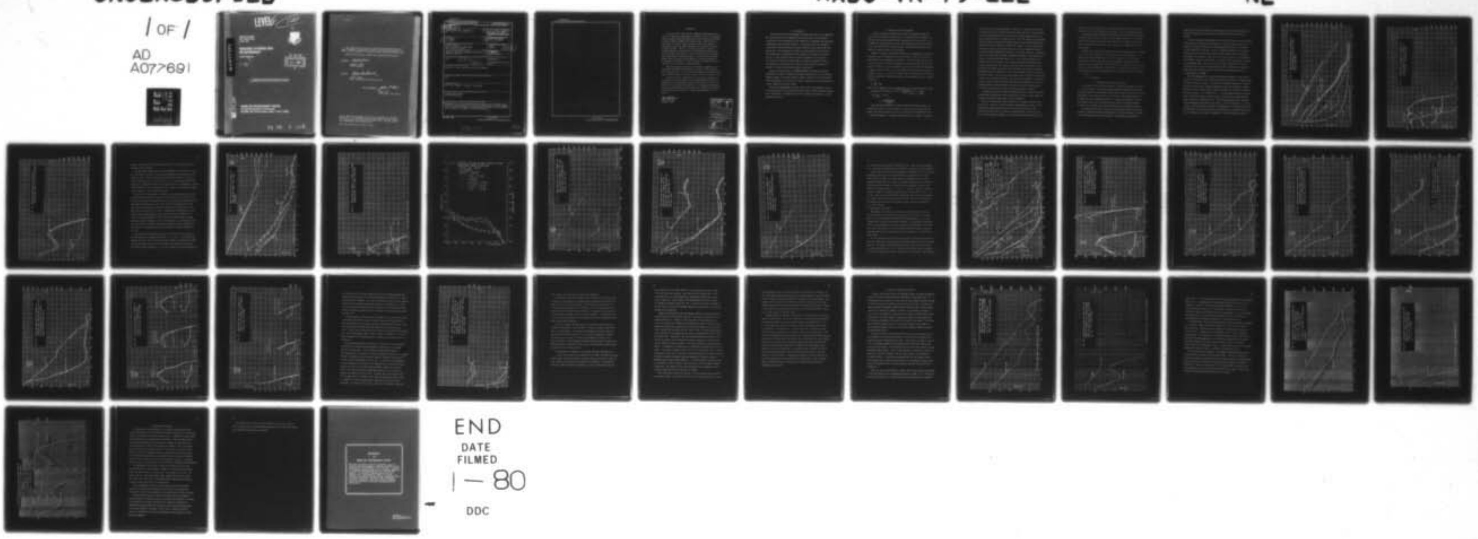

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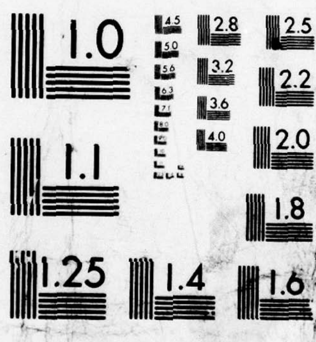

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RADC-TR-79-222
Final Technical Report
October 1979

GROUND SYSTEMS FOR HF ANTENNAS

Purdue University

W. L. Weeks
C. L. Chen

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ROME AIR DEVELOPMENT CENTER
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Current Distributions

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Measurements on a full-scale model ground system on actual earth were found to agree at least qualitatively with results predicted in an earlier computer study. Such ground systems of suitable length may enhance the field strength of HF antennas at low angles by at lease 10 percent.

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EVALUATION

This Final Report under Contract F19628-78-C-0057 describes the results of experimental measurements undertaken to verify corresponding results previously obtained theoretically and numerically under another contract (F19628-76-C-0086) whose objective was to determine the effectiveness of relatively small horizontal ground wire systems in improving the low angle radiation/reception for vertically polarized HF antenna systems. The work is directly applicable to the cost-effective design of ground systems for long-range OTH communications and surveillance radar antennas. Full scale models over real earths were investigated in these measurements. Good qualitative agreement between theory and experiment was obtained. The large uncertainty in the electrical properties of the earth near the antenna apparently precluded more quantitatively precise agreement.

Antenna performance proved also to be markedly dependent on the lengths and spacings of the ground wires, as well as their position with respect to earth. For any given ground system it was established that the phase constant of the wire currents can vary from wire to wire.

Variations typically experienced in the electrical parameters of the earth over the entire extent of the ground system are shown to be responsible for correspondingly significant variations in the distribution of current along the ground wires. This suggests that measured rather than calculated current distributions on the ground wires would often be required in practice for reliable determinations of field patterns.

Charles J. Drane
CHARLES J. DRANE
Project Engineer

1. Introduction

The HF portion of the electromagnetic spectrum continues to be of importance for long distance military communication and surveillance. The ionospheric reflections at these frequencies, while occasionally troublesome, make long-range communication cost and energy effective. To make best use of the ionospheric interactions, radiation should be vertically polarized with strong fields near the horizon. The incorporation of extensive ground systems for the antennas offers some hope of increasing the field strength at low angles by filling in the null in that direction caused by imperfect conductivity of the earth. This study and a previous one have sought to evaluate the potential gains to be accrued by the incorporation of relatively small horizontal ground wire systems in vertically polarized HF antenna installations.

Under a previous contract (F 19628-76-C-0086), the subject was studied theoretically, primarily through the development and application of an extensive computer program. The present contract primarily supported a program of experimental measurements to verify that the computer generated results were applicable to real systems and the actual earth.

Most of the measurements were those of the current distribution on ground wires installed in a sod field near the Purdue Airport in West Lafayette, Indiana, at two frequencies: 13.56 MHz and 27.12 MHz. Equipment was housed in a trailer parked near the site.

2. Measurement of Earth Parameters

In order to compare the theoretical results with experimental data for the current distributions on ground wires in an actual field in Indiana, it is necessary to have earth parameter values representative of the specific site. In common with previous workers we have found the determination of such values to be a very difficult and frustrating task. Each measurement depends upon a number of uncertain conditions and variables.

Based on a review of the possible methods for the measurement of the earth parameters, and prior experience with some of them, the "wave tilt" method of measurement of earth parameters was selected. It has been shown that the electric field set up by a vertical antenna over an actual earth has a radial component E_ρ as well as a vertical component, E_z; the ratio of these two components is $E_z/E_\rho = (\varepsilon/\varepsilon_o)^{1/2}$, where $\varepsilon/\varepsilon_o$ is the complex relative dielectric constant of the earth: $\varepsilon/\varepsilon_o = \varepsilon_r - j\,\sigma/\omega\varepsilon_o$. It follows that if the ratio of the field components is measured in amplitude and phase, the earth parameters may be obtained as follows:

$$\text{Let } \frac{E_z}{E_\rho} = A\underline{/\theta}$$

where A is the measured relative amplitude and θ is the measured relative phase.

$$\text{Then } A\underline{/\theta} = \sqrt{\varepsilon_r - j\,\sigma/\omega\varepsilon_o} = \sqrt{\varepsilon_r}\,\sqrt[4]{1 + \left(\frac{\sigma}{\omega\varepsilon_r\varepsilon_o}\right)^2}\,\underline{\Big/\frac{1}{2}\tan^{-1}\left(-\frac{\sigma}{\omega\varepsilon_r\varepsilon_o}\right)}$$

$$\text{Thus } \frac{\sigma}{\omega\varepsilon_r\varepsilon_o} = -\tan 2\theta$$

$$\varepsilon_r = \frac{A^2}{\sqrt{1 + \left(\frac{\sigma}{\omega\varepsilon_r\varepsilon_o}\right)^2}}$$

The actual measurement of the relative amplitude and phase was done with equipment as follows: A metal box about 25 x 50 x 20 cms was constructed to support receiving antennas consisting of a vertical and a horizontal brass rod in insulating supports. One support held the horizontal rod about 7 cms above the ground. Each rod was approximately 1 meter long. One end of each rod was fed through identical fittings into identical 100KΩ resistors to the box ground, so that a good approximation to the open circuit voltage induced on each rod could be measured across the 100KΩ resistors. These two signals were led through identical coaxial fittings, then through identical 8 meter long RG 58/U cables terminated in 50 ohms attached to special tee fittings. These fittings are designed to accept the special probes that lead to the two independent channels of a Hewlett-Packard 8405A Vector Voltmeter. This vector voltmeter is a sampling type of instrument which indicates the absolute amplitudes in each channel with signals in the range from about 20μV to 1V. It also reads the phase of one channel relative to the other. Thus, leading the signal from the base of the vertical rod antenna to, say, channel A, and the signal from the base of the horizontal rod antenna to channel B, the instrument is well suited to read the amplitude and relative phase of the open circuit voltages from the vertical and horizontal antenna. When these receiving antenna rods are properly oriented with respect to the transmitting antenna, their open circuit voltages are proportional to the horizontal radial and vertical electric fields respectively, so that the measured quantities introduced above, the ratio, A, and the relative phase, θ, are easily determined from the meter readings of the vector voltmeter.

A quarter wave vertical transmitting antenna was set up (without horizontal ground wires) and energized, and the receiving box placed at various positions ranging from about 8m to about 30m from the transmitter.

While this system seems close to ideal at first thought, there are some difficulties. These are 1) the influence of the experimenter, cables, instrumentation and extraneous objects on the field ratio at the rods, 2) the variability of the direct or incidental ground connections of the box to the earth, 3) the different impedance of the two antenna rods because of their different proximity and orientation with respect to ground, 4) the inherent phase error due to the finite length of the horizontal rod in the propagating field.

An attempt was made to overcome the latter two difficulties by a redesign in which both antenna rods were held at 45° with respect to ground. This attempt largely failed because of the poor "conditioning" of the numbers which must be used in calculating the parameters (i.e., subtraction of two numbers which are almost equal).

Moreover, there was some evidence that the earth parameters were not uniform over the site and, furthermore, varied from day to day with the weather. As a result of all these difficulties, in spite of a large number of trials and refinements, the error associated with our measurements of earth parameters appears to be as large as 100%. The differences of the parameters at the two frequencies selected (13.56MHz and 27.12MHz) were not statistically different. We conclude then that the earth parameters at our experimental site were as follows:

$\varepsilon_r = 8 \pm 4$

$\sigma = 5 \pm 4$ millimhos/m.

3. Measurement of Current Distributions

The signal at the two desired frequenices (13.56 and 27.12MHz) was provided by a Type 101 General Radio Standard signal generator followed by an ENI broad band power amplifier; an additional Stan-Com 100 watt amplifier was also available when needed. This signal generated in the trailer was fed through 100 feet of RG 58/U cable to the transmitting antennas. A phase (and amplitude) reference was provided either by a tee connection at the output of the signal generator or (later) by a reference loop fixed at the base of the transmitting antenna.

The phase and amplitude of the current in the ground wires was measured by holding a shielded loop antenna (approximately 75 cm^2 area) adjacent to the wire in both horizontal and vertical orientation. As measurements progressed, it became clear that the horizontal orientation gave results more representative of the current distributions, especially at positions close to the transmitting antenna.

Literally hundreds of independent sets of current distribution data were taken, partly because of the different configurations of interest and partly to try to identify the important factors which caused repeatable but day to day and spot to spot variability in the data. Scatter in apparently smooth data was observed due to ground wire position with respect to ground surface, the type of ground and ground cover immediately under the wire at a given position, and the dampness of the ground. Because of the scatter in the data, we will not attempt to include all experimental data. Rather, we will present typical distributions, with an indication of the variability and spread of the data. Perhaps surprisingly, the phase data points typically show less scatter than the amplitude data points.

A. Measurements at 13.56MHz

The first measurements of current distribution were made on a system consisting of a single quarter wave vertical having a single, long (66 or 75 foot) ground wire open circuited at the end. The wire was TS #14 gauge insulated wire laid out and held in position with insulating stand-offs driven into the ground. Measurements were taken at regular intervals along the ground wire (usually at one foot or two foot intervals). As is shown in Fig. 1, the phase data revealed that except within a half wave length or so from the open circuited end, the phase distributions is that of a traveling wave (i.e., linear phase progression with distance) with the wavelength along the wire less than λ_o, the free space value: $\lambda_w = (.63 \pm .03)\lambda_o$. The amplitude was also found to decrease more or less as would be expected (the ideal 1/r variation that would be expected near a sinusoidal vertical current is indicated on the graphs for comparison). Near the open end of the wire

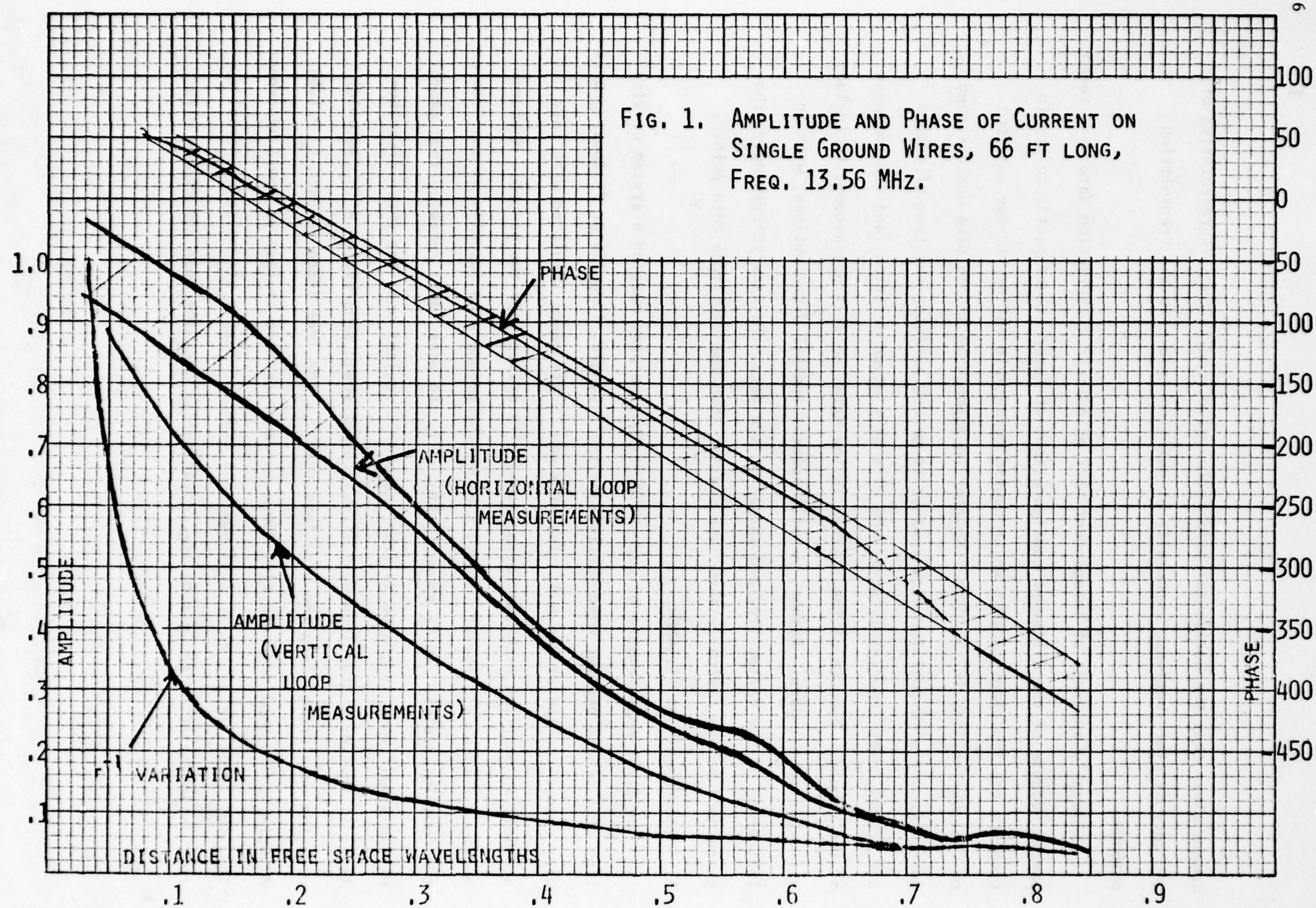


FIG. 1. AMPLITUDE AND PHASE OF CURRENT ON SINGLE GROUND WIRES, 66 FT LONG, FREQ. 13.56 MHz.

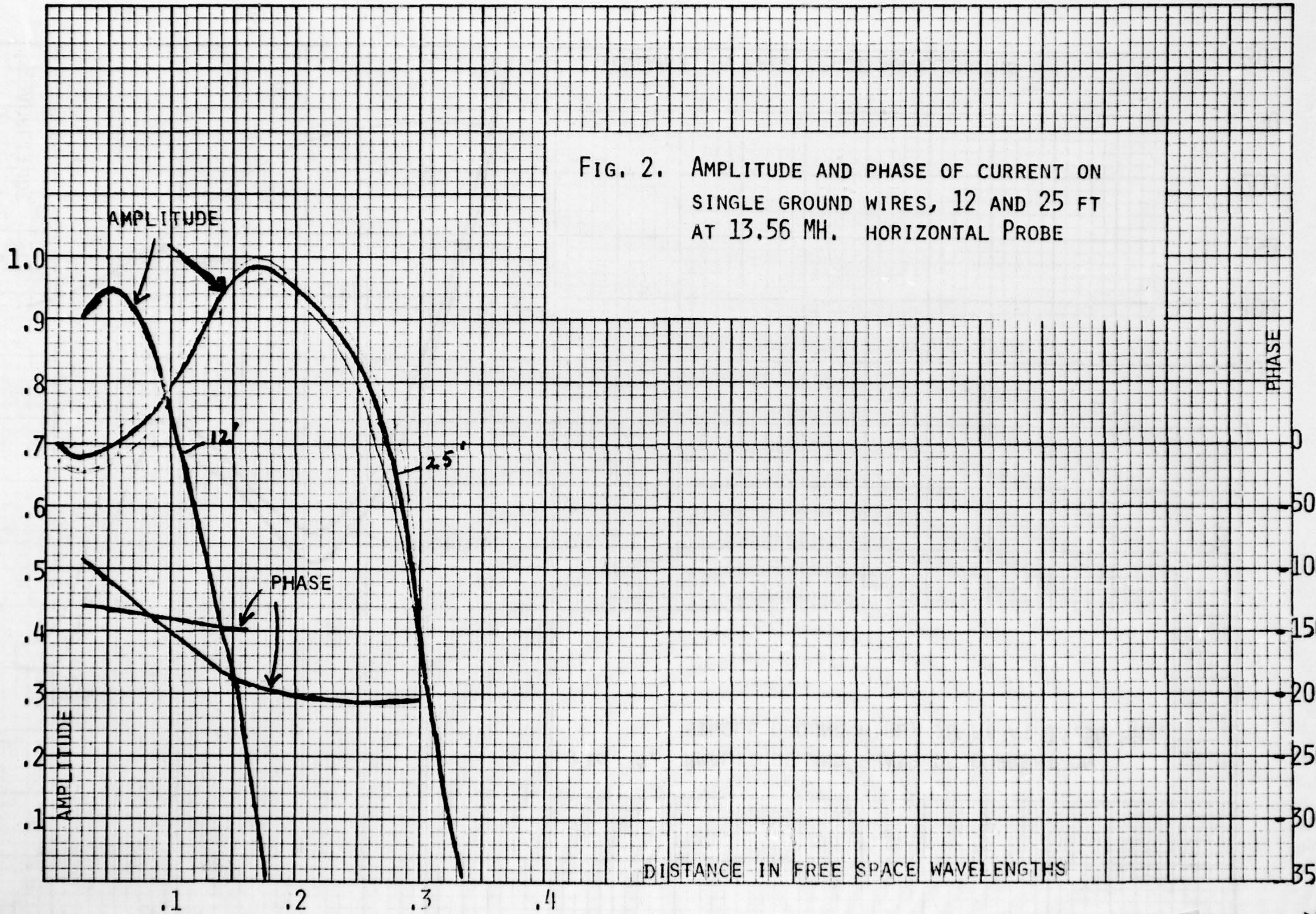


FIG. 2. AMPLITUDE AND PHASE OF CURRENT ON SINGLE GROUND WIRES, 12 AND 25 FT AT 13.56 MH. HORIZONTAL PROBE

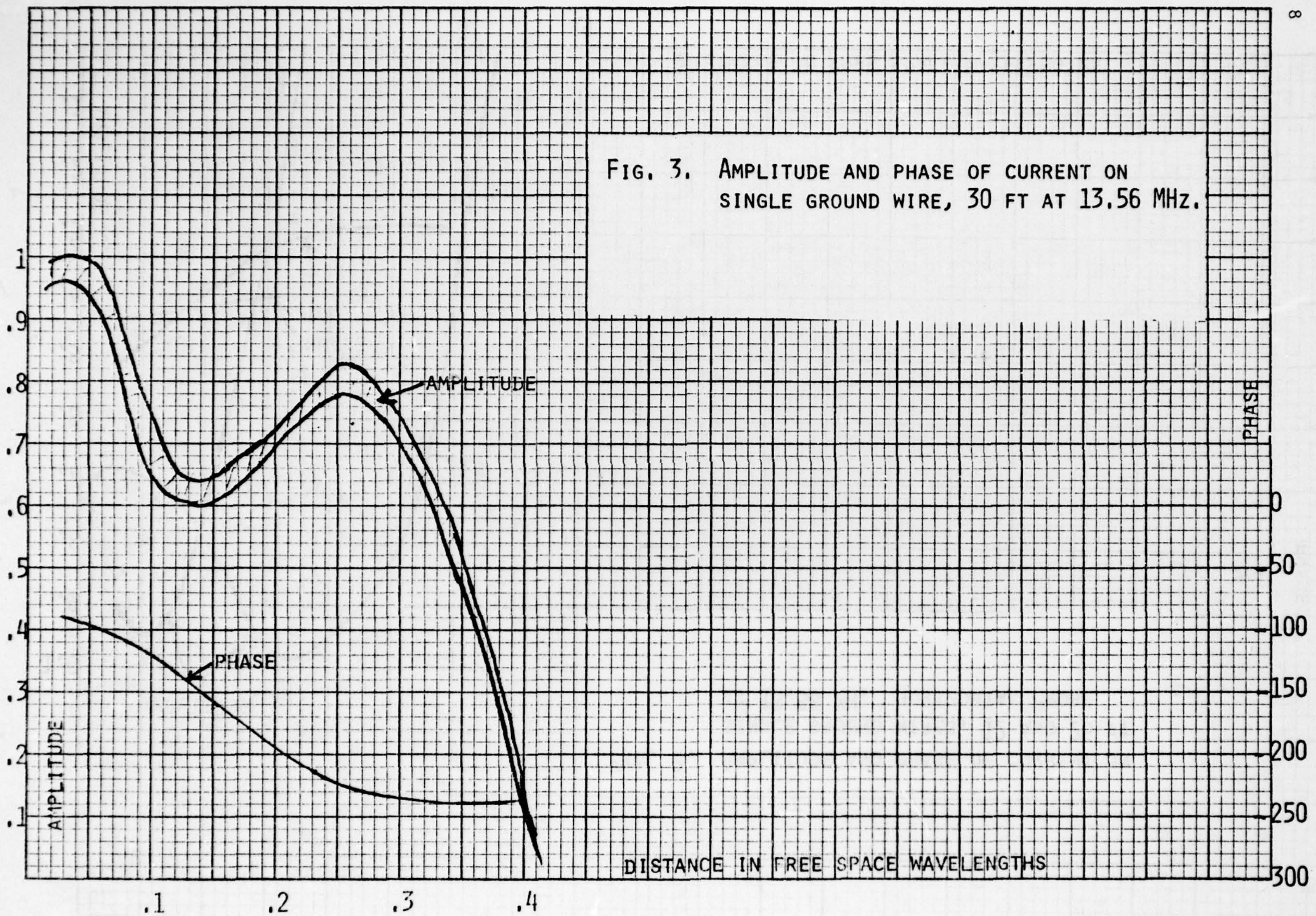


FIG. 3. AMPLITUDE AND PHASE OF CURRENT ON SINGLE GROUND WIRE, 30 FT AT 13.56 MHz.

however, the effect of a reflected wave shows itself in the tendency toward a standing wave distribution.

The phase data indicated that a quarter wavelength on the ground wire would be in the range 11-13 feet, so the wire was shortened to study the effects when the ground wire is about a half wavelength long as well as when it is about a quarter wavelength long. As shown in Figs. 2 & 3, the current distributions change from a predominately traveling wave distribution to a predominately standing wave distribution, with the phase more or less constant near the peaks and changing very rapidly in the vicinity of the nulls.

The next set of measurements was made with a single quarter wave vertical antenna and three ground wires running out the same side of the vertical. The current distributions were checked both with a strictly radial configuration with approximately 45° between the radial wires and with a configuration in which after about 5 feet, the outer wires bent inward so as to run parallel to the center wire at a separation of 1 meter. Although small differences were noted between these two configurations, the significance of the differences is in doubt since the distributions on the two outer wires had as great or greater differences between themselves. This lack of symmetry in a configuration which would be symmetric in an ideal situation was observed repeatedly; presumably it was caused by the nonuniformity of the earth and of the ground connections at the site.

While the general characteristics of the distributions on the three wires were the same as on a single wire (see Figs. 4, 5 and 6), the details were somewhat different. When all three wires had a length of approximately 76 feet, the wavelength along the center wire was found to be longer than that of the distribution along a single wire: $\lambda_{cw} = (.75 \pm .035)\lambda_o$, while the wavelength on

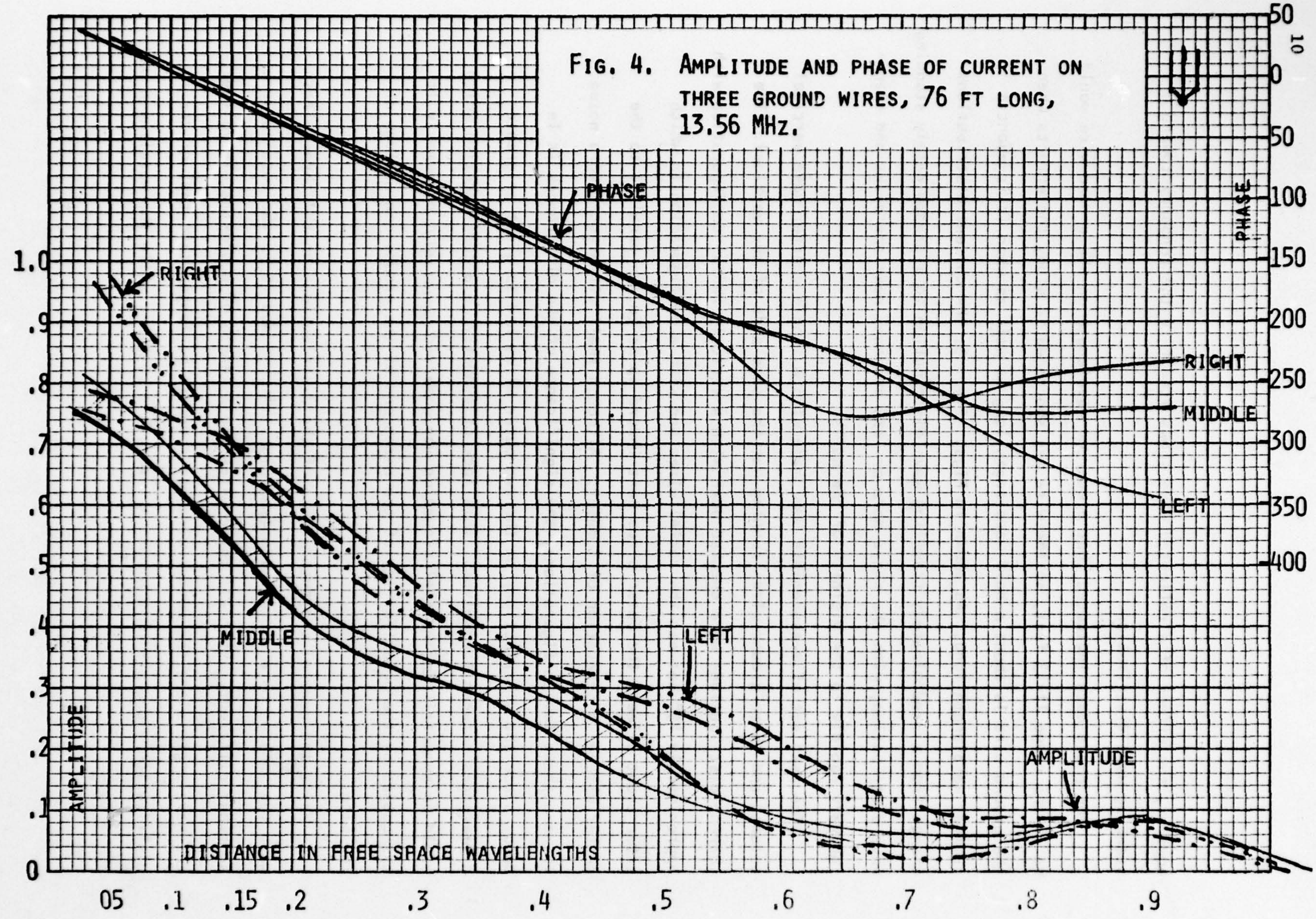


Fig. 4. Amplitude and phase of current on three ground wires, 76 ft long, 13.56 MHz.
PHASE
RIGHT
MIDDLE
LEFT
AMPLITUDE
DISTANCE IN FREE SPACE WAVELENGTHS
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
05
.1
.15
.2
.3
.4
.5
.6
.7
.8
.9
50
10
0
50
100
150
200
250
300
350
400

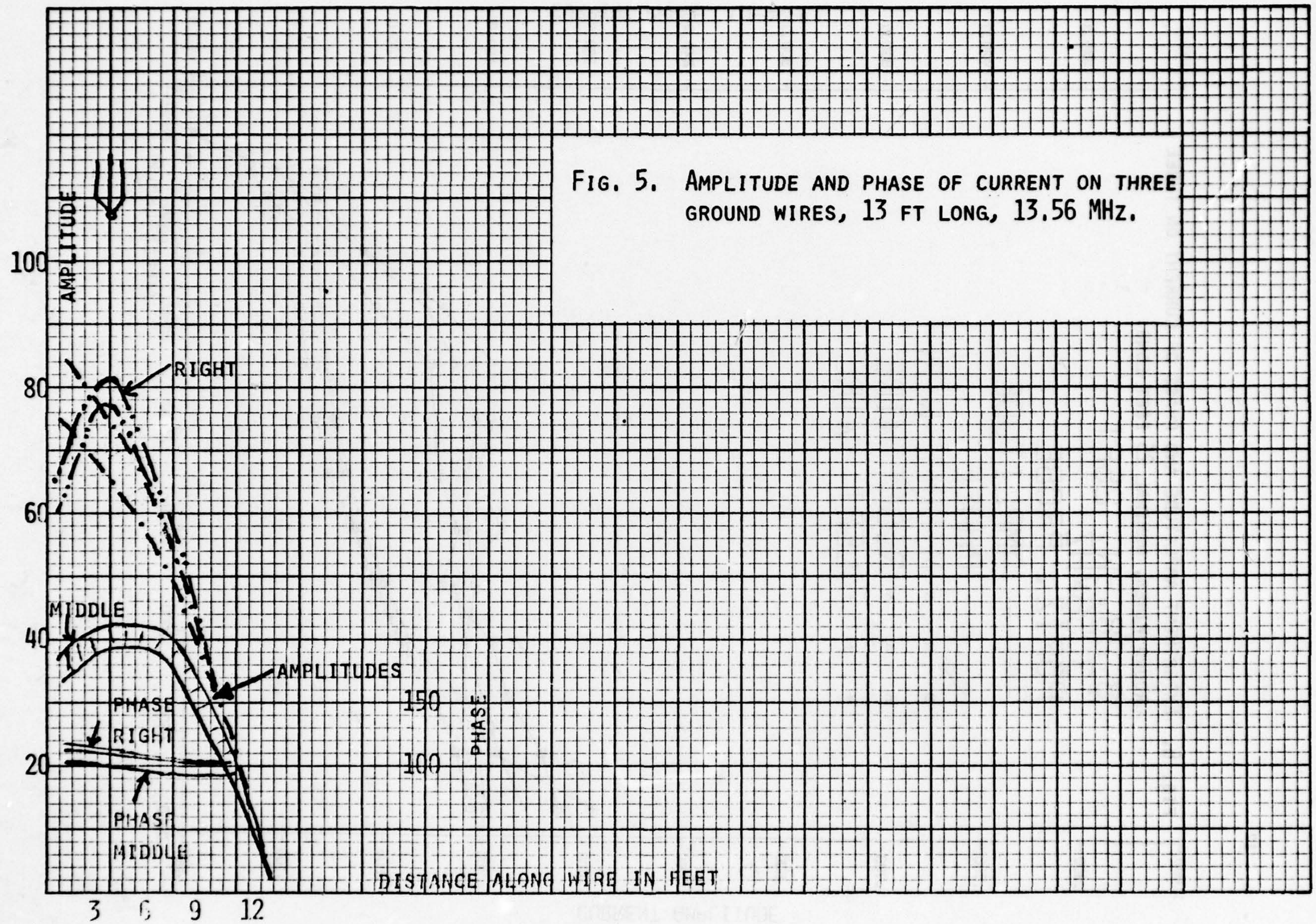
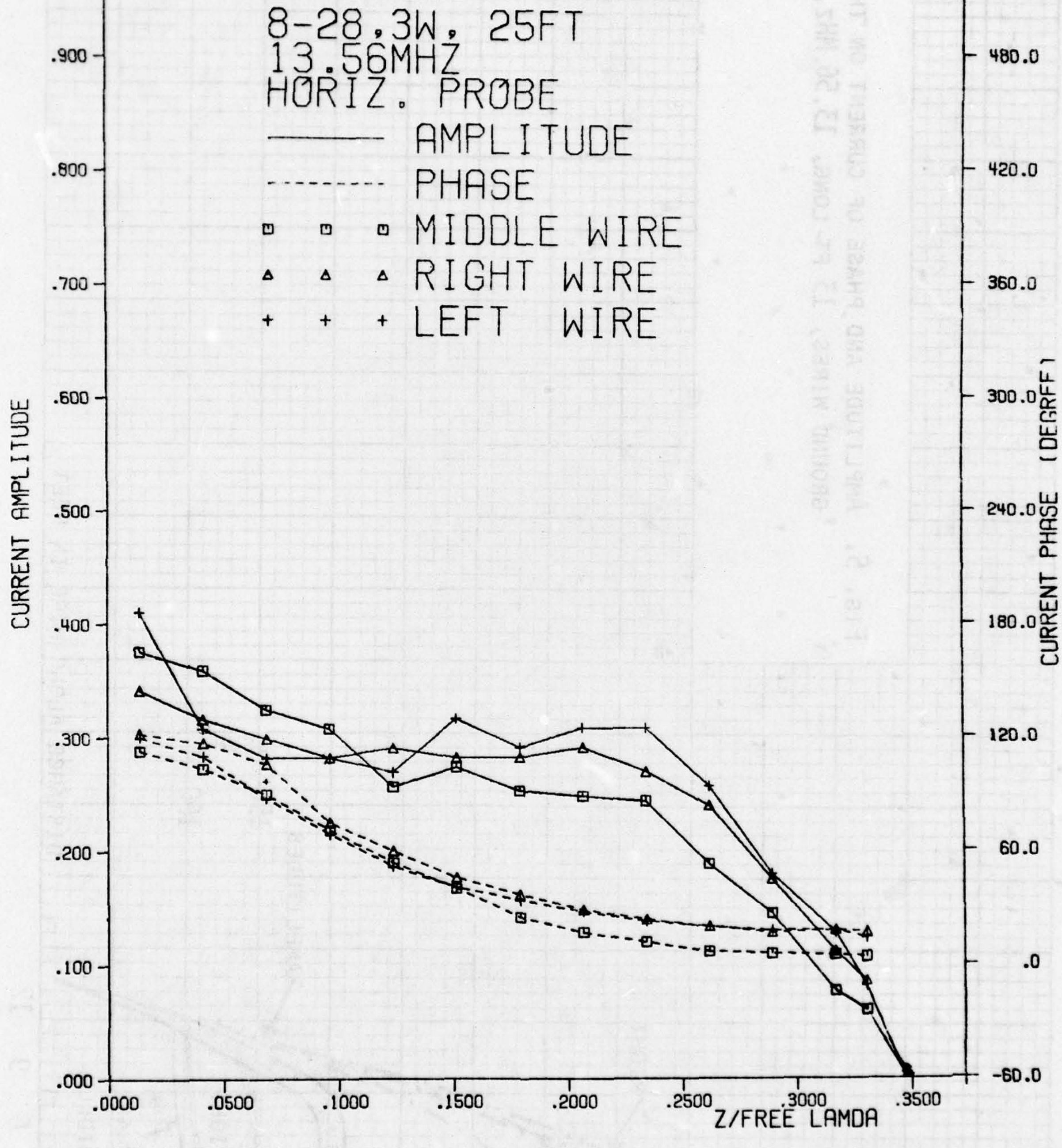


FIG. 5. AMPLITUDE AND PHASE OF CURRENT ON THREE GROUND WIRES, 13 FT LONG, 13.56 MHz.

FIG. 6. EXPERIMENT AMPLITUDE AND PHASE OF CURRENT ON THREE GROUND WIRES, NOMINAL 25 FEET LONG.



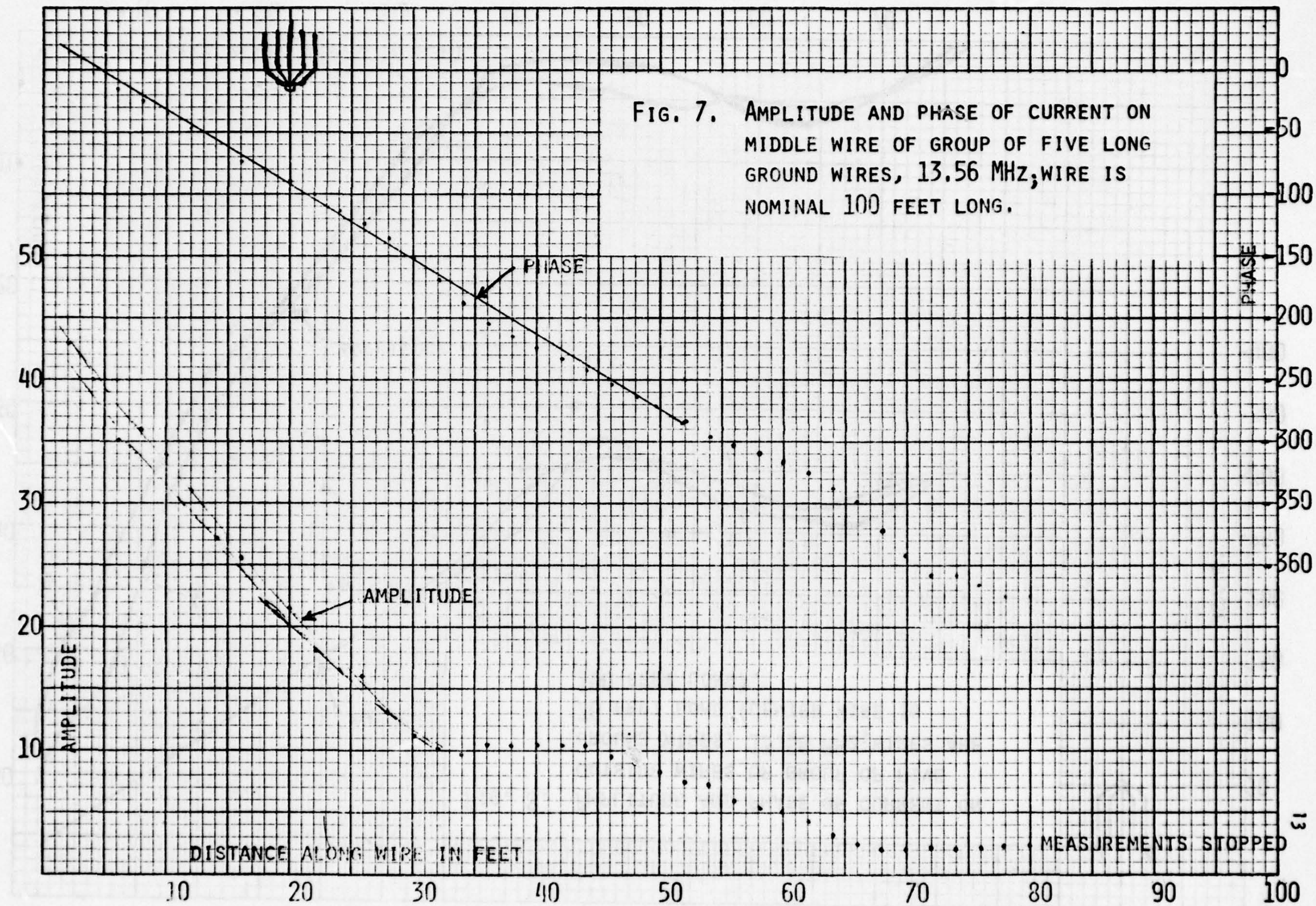


Fig. 7. Amplitude and phase of current on middle wire of group of five long ground wires, 13.56 MHz; wire is nominal 100 feet long.

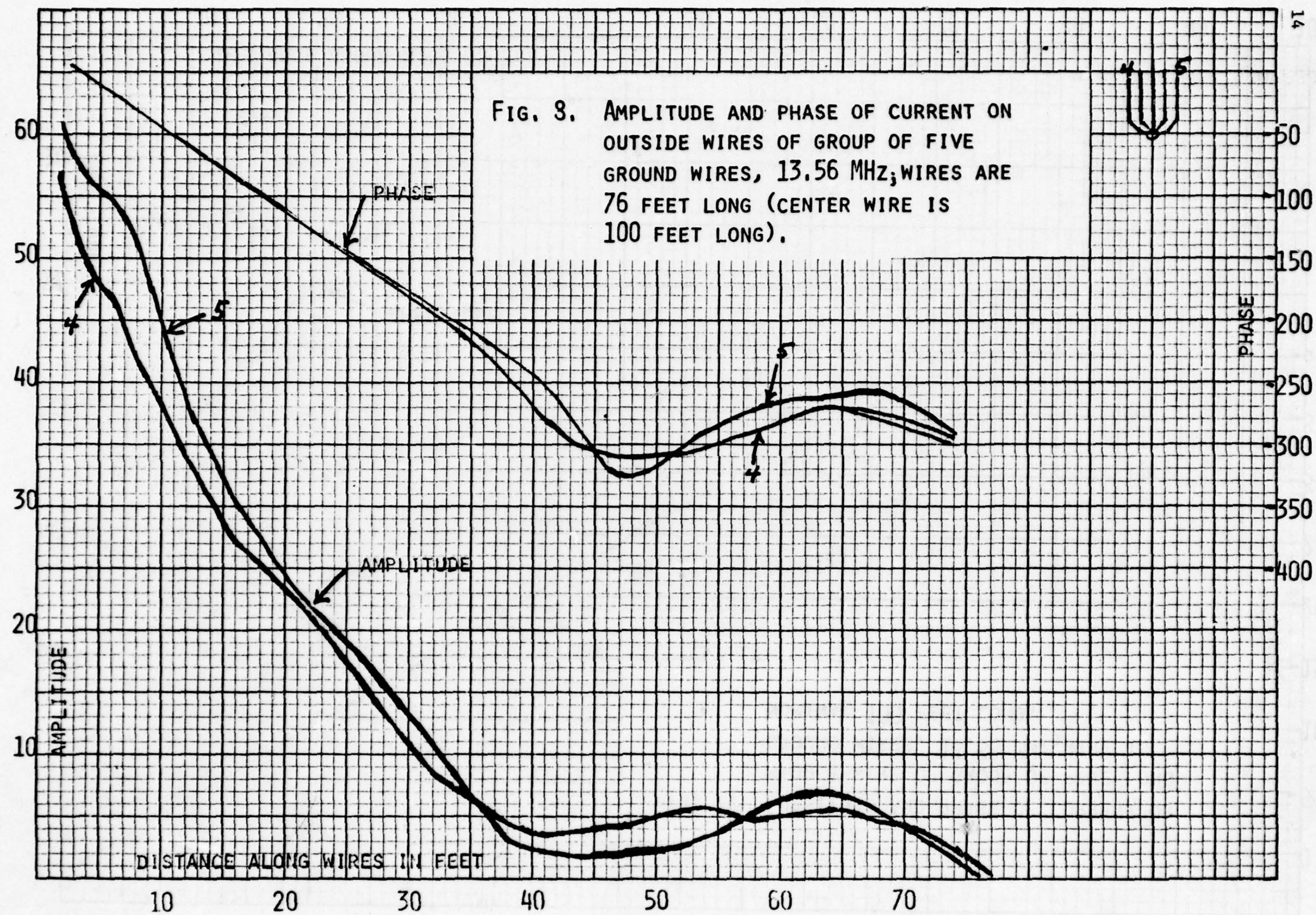


FIG. 8. AMPLITUDE AND PHASE OF CURRENT ON OUTSIDE WIRES OF GROUP OF FIVE GROUND WIRES, 13.56 MHz; WIRES ARE 76 FEET LONG (CENTER WIRE IS 100 FEET LONG).

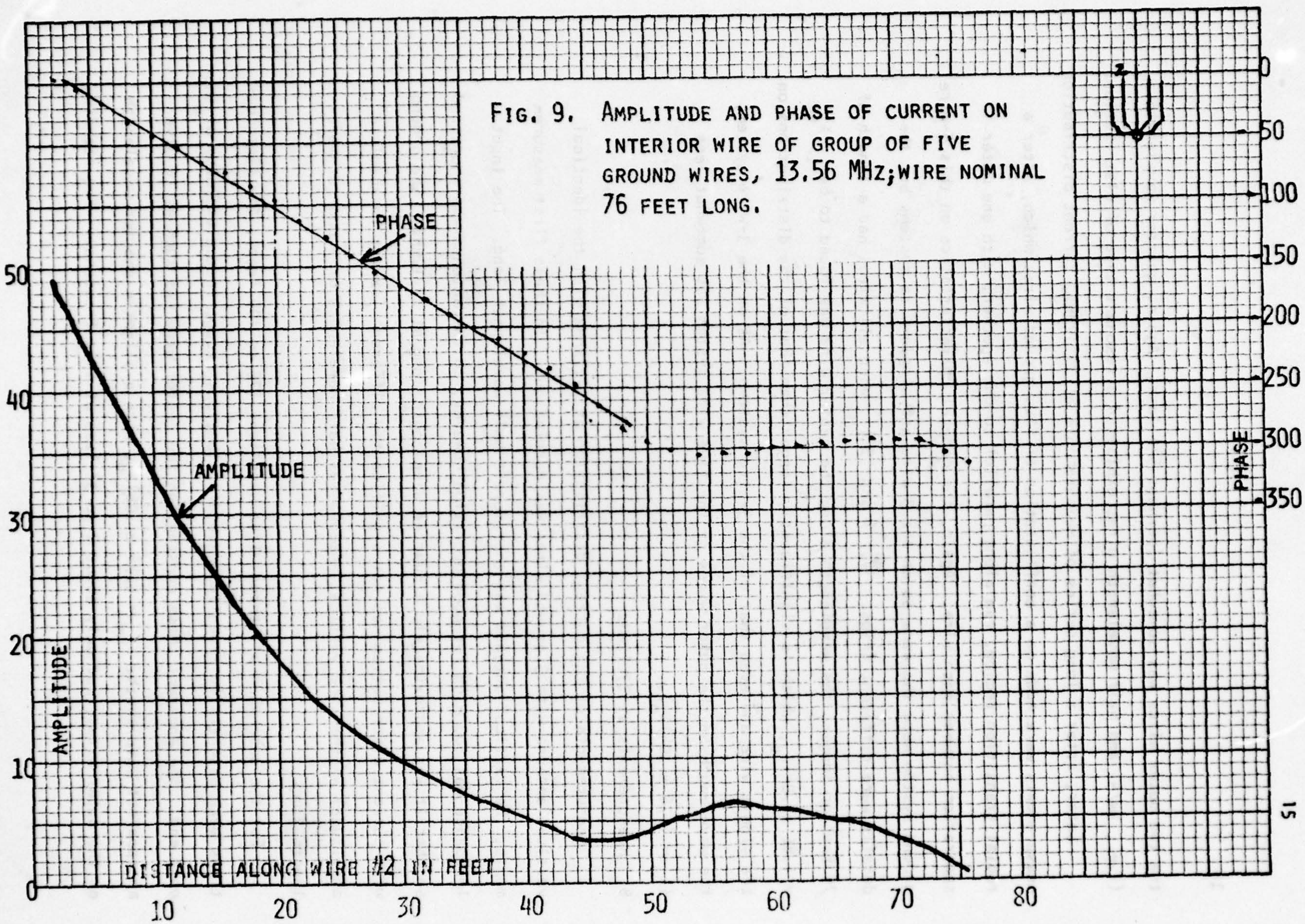


Fig. 9. Amplitude and phase of current on interior wire of group of five ground wires, 13.56 MHz; wire nominal 76 feet long.

the two outer wires was somewhat (perhaps 5%) less. Again, quarter wavelength (i.e., $\lambda w/4$) and half wavelength wires exhibited a resonant type of distribution.

Later, after a long series of measurements at 27.12MHz, current distribution measurements were made on a configuration of five ground wires which, after a radial transition region, ran along parallel to one another, with one meter separation between each wire. Again, the general characteristics on this 5-wire ground system were the same as on the 3-wire and single-wire systems but the details were different (Figs. 7, 8 and 9). When all wires had a length of 75 feet or longer, the wavelength along the center wire was found to be: $\lambda_{cw} = (.86 \pm .04)\lambda_o$, which is significantly longer than that of the distributions on the single wire and even that of the 3-wire systems. As on the 3-wire system, the wavelength on the outer wires of the five wire system was somewhat less ($\lambda_w = (.76 \pm .04)\lambda_o$).

B. Measurements at 27.12MHz

Measurements of the current distribution at 27.12MHz with the identical vertical antenna with 3 ground wires was carried out. In these first measurements, the vertical antenna was therefore a half wavelength long. The input impedance was too high for good operation however, so the antenna was shortened so that it was approximately a quarter wavelength long at 27.12MHz. The ground wire current distribution was not significantly different (except in absolute amplitude) whether the vertical antenna was half wavelength or a quarter wavelength long.

For the case when all three wires were long (75 to 100 feet), the distributions were essentially traveling wave distributions except in the vicinity of the open end. The apparent phase constant on the center wire was such as to give an apparent wavelength, $\lambda_{cw} = (.76 \pm .06)\lambda_o$, with a slightly shorter wavelength on the outer wires, but only about 2 to 3% less at this frequency. The standing

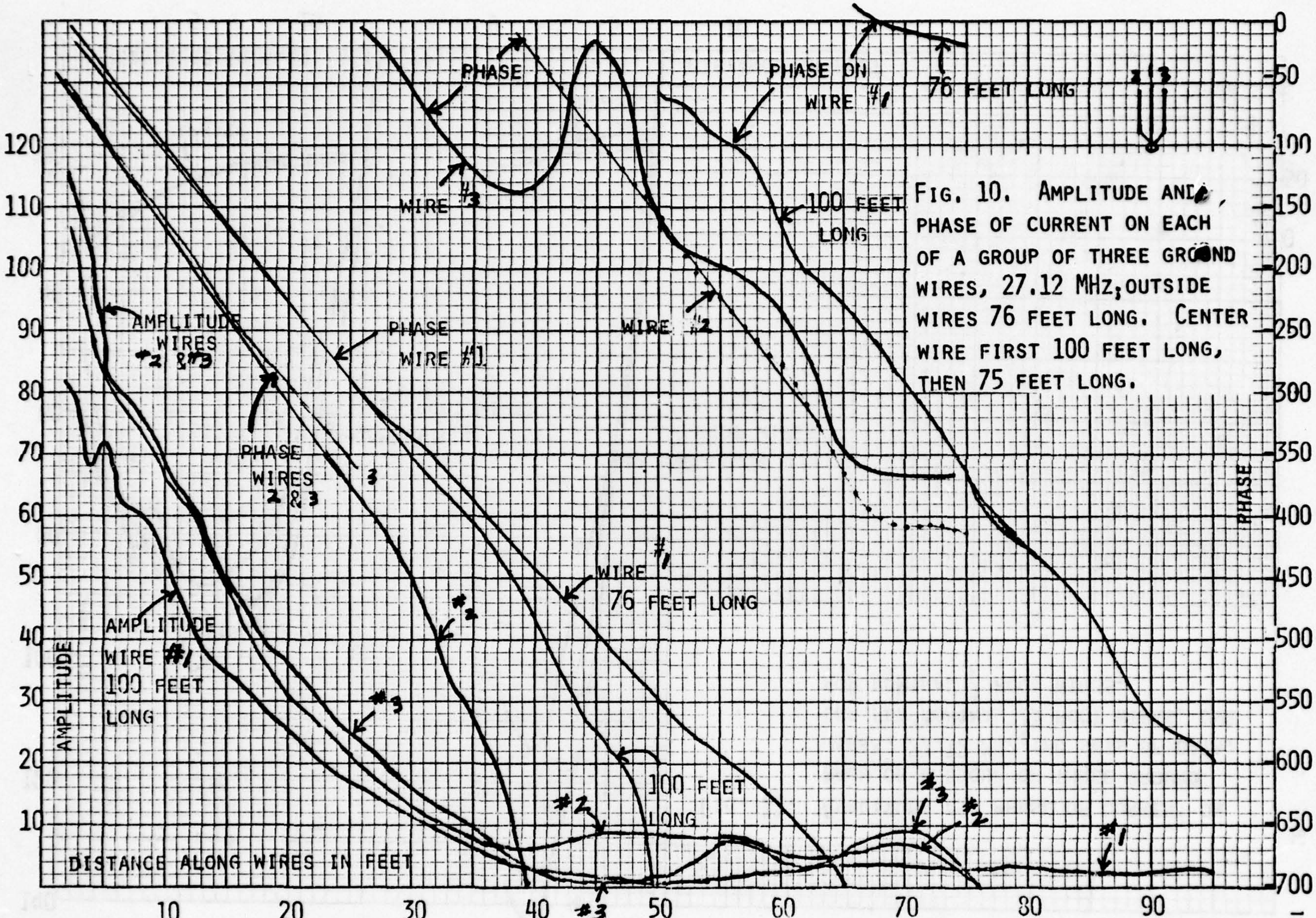


FIG. 10. AMPLITUDE AND PHASE OF CURRENT ON EACH OF A GROUP OF THREE GROUND WIRES, 27.12 MHz; OUTSIDE WIRES 76 FEET LONG. CENTER WIRE FIRST 100 FEET LONG, THEN 75 FEET LONG.

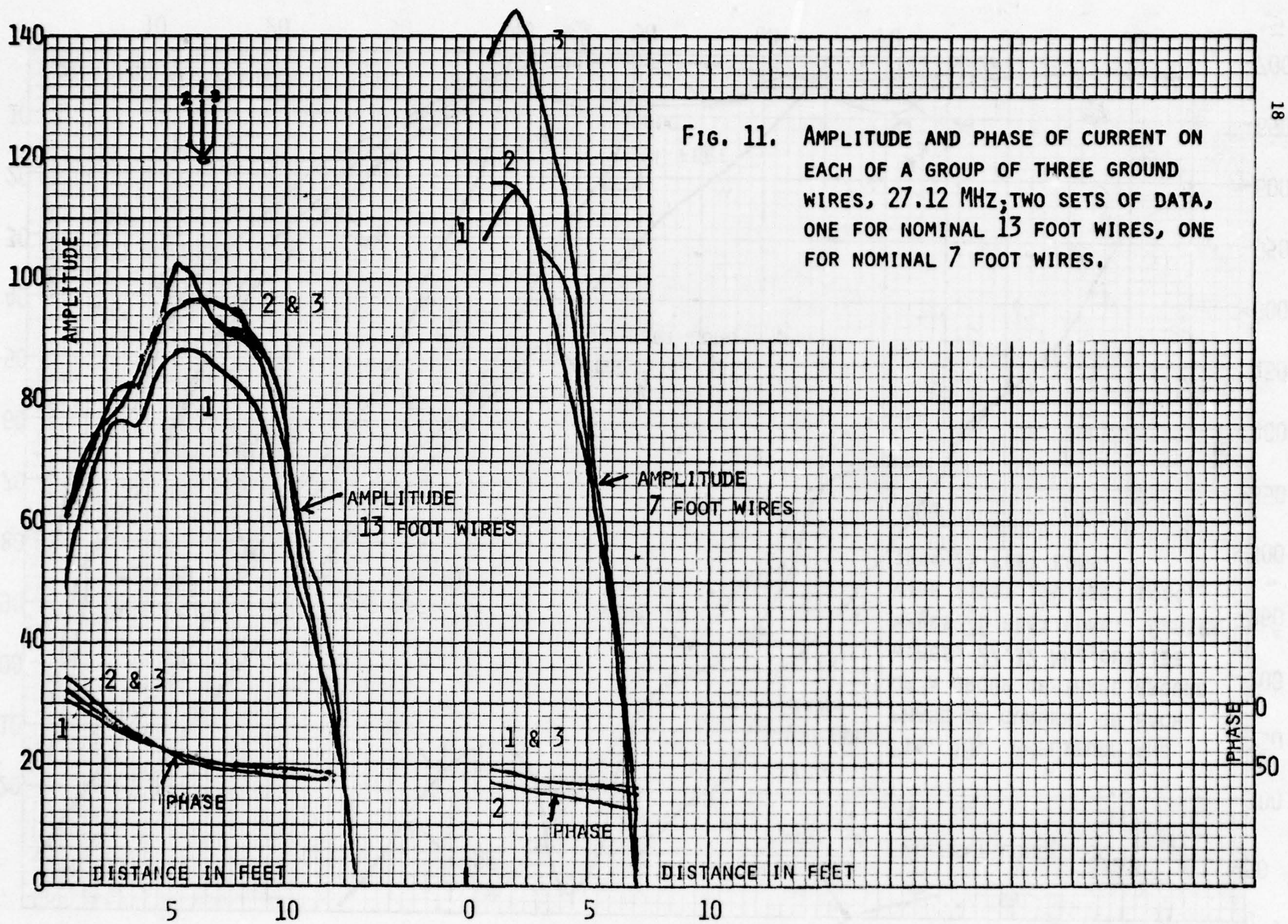


FIG. 11. AMPLITUDE AND PHASE OF CURRENT ON EACH OF A GROUP OF THREE GROUND WIRES, 27.12 MHz; TWO SETS OF DATA, ONE FOR NOMINAL 13 FOOT WIRES, ONE FOR NOMINAL 7 FOOT WIRES.

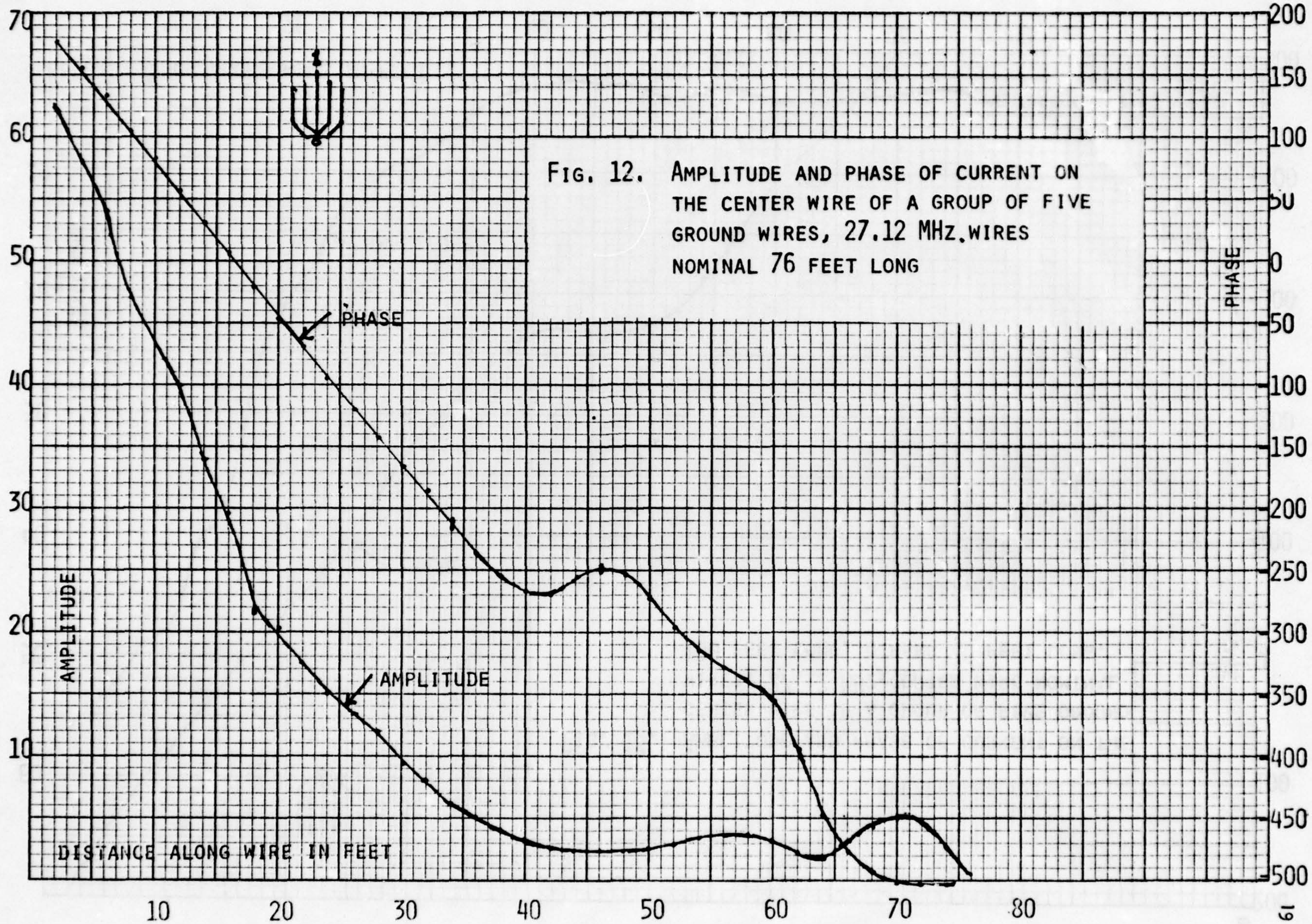


FIG. 12. AMPLITUDE AND PHASE OF CURRENT ON THE CENTER WIRE OF A GROUP OF FIVE GROUND WIRES, 27.12 MHz.WIRES NOMINAL 76 FEET LONG

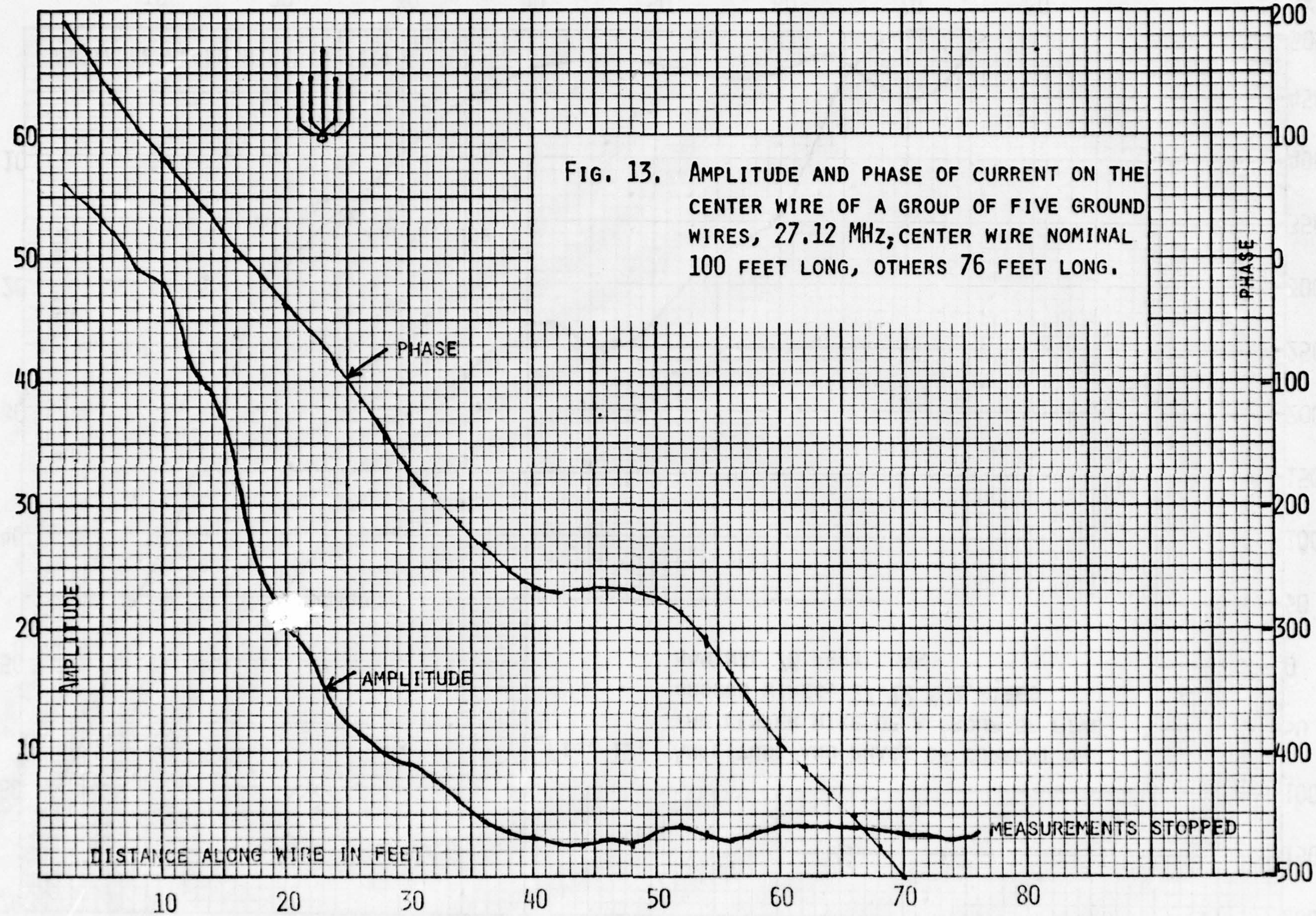


Fig. 13. Amplitude and phase of current on the center wire of a group of five ground wires, 27.12 MHz; center wire nominal 100 feet long, others 76 feet long.

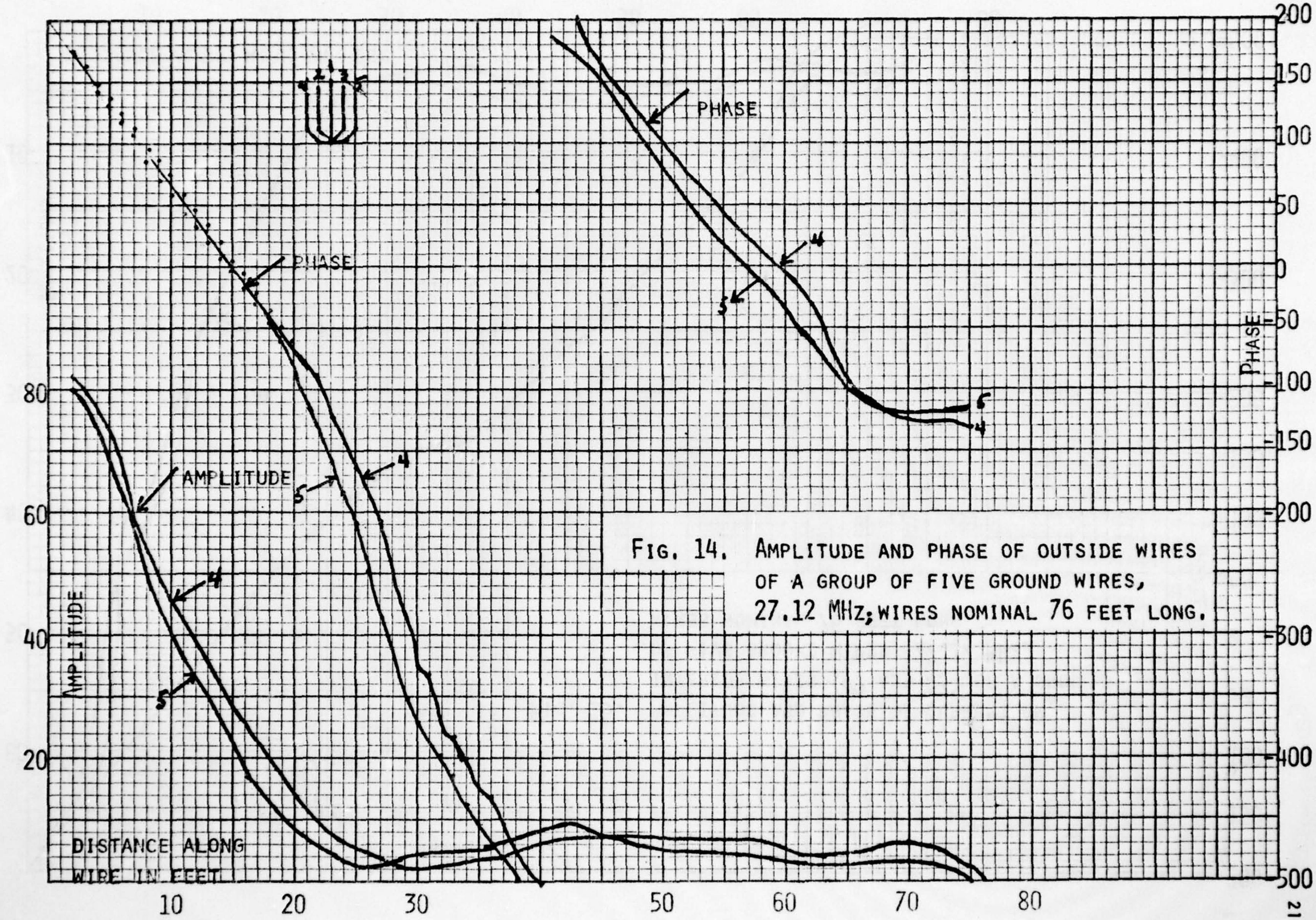


Fig. 14. Amplitude and phase of outside wires of a group of five ground wires, 27.12 MHz; wires nominal 76 feet long.

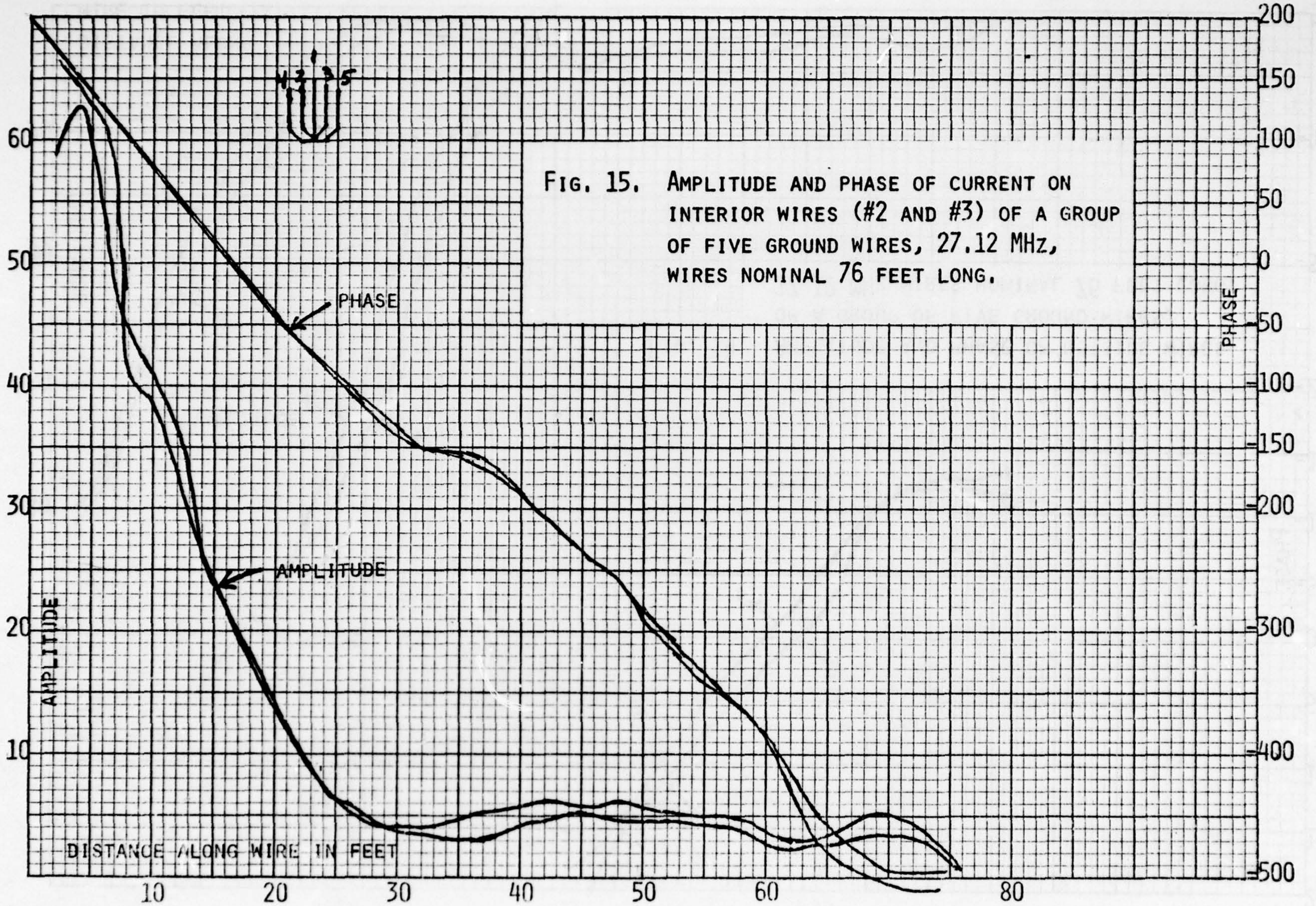


FIG. 15. AMPLITUDE AND PHASE OF CURRENT ON INTERIOR WIRES (#2 AND #3) OF A GROUP OF FIVE GROUND WIRES, 27.12 MHz, WIRES NOMINAL 76 FEET LONG.

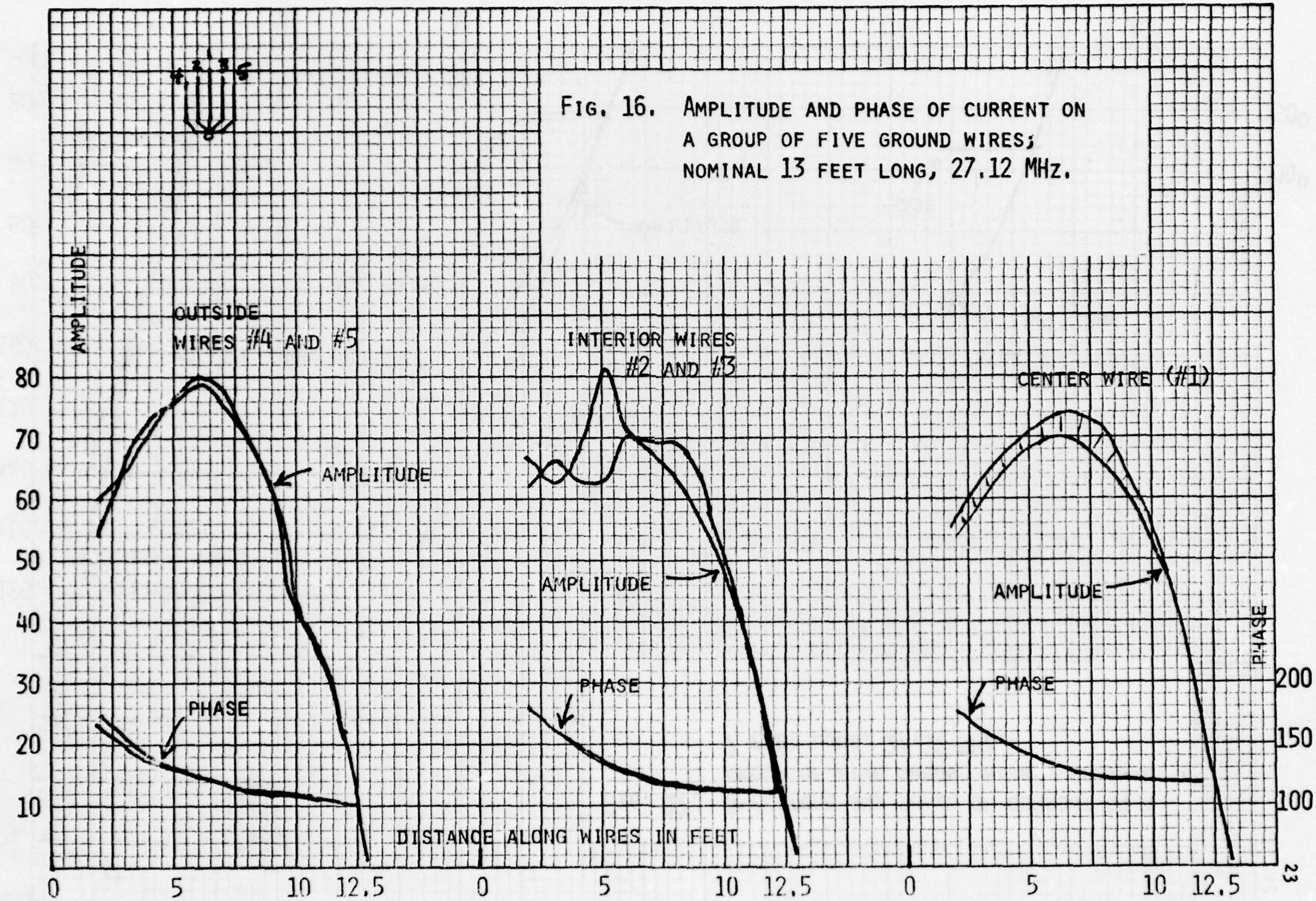


FIG. 16. AMPLITUDE AND PHASE OF CURRENT ON A GROUP OF FIVE GROUND WIRES; NOMINAL 13 FEET LONG, 27.12 MHz.

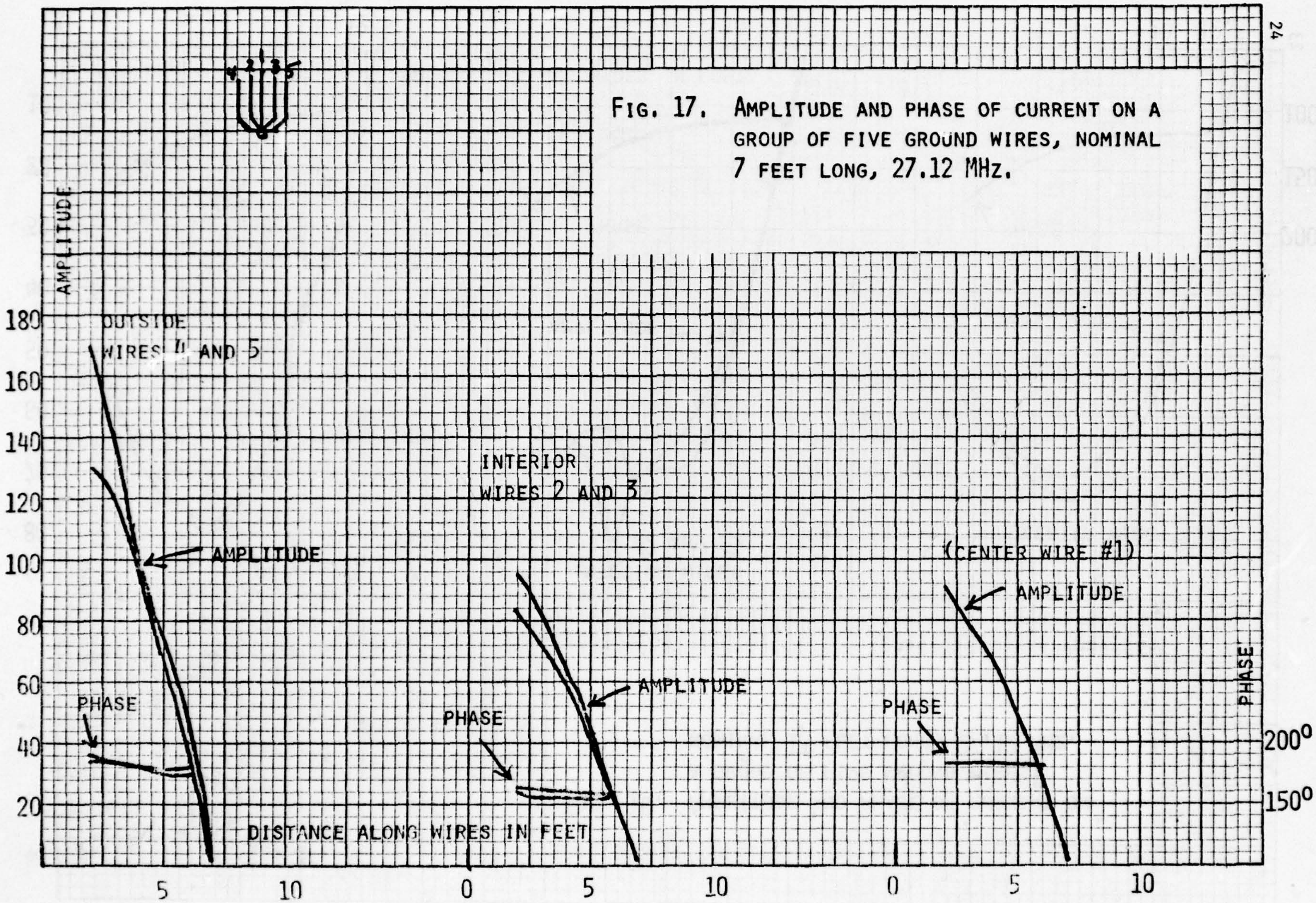


FIG. 17. AMPLITUDE AND PHASE OF CURRENT ON A GROUP OF FIVE GROUND WIRES, NOMINAL 7 FEET LONG, 27.12 MHz.

wave characteristics (sine-like amplitude variation with constant phase near loops) were more prominent (Fig. 10) near the open circuited ends (i.e., more prominent than at 13.56MHz). The wires were shortened so that they were approximately one-half wavelength long and then one quarter wavelength long. These distributions have the features of the sinusoidal, resonant type distributions having a wavelength consistent with that indicated by the traveling wave phase data (Fig. 11).

When the number of ground wires was increased to five, with one meter separation between each (after a radial transition region near the feed point), the general features of the measured current distributions were the same. However, the apparent wavelength along the inside wires was found to be $\lambda_{cw} = (.81 \pm .04)\lambda_0$, while the wavelength on the outer wires was about 5 to 6 percent less. Typical experimental data is shown in Figs. 12 through 17. It is clear that the presence of the neighboring wires influences the propagation on the center wire.

As was pointed out earlier, the current in the ground wires was measured with the aid of a shielded loop held adjacent to the wires in a horizontal position at ground level. This orientation was employed in order to minimize the "contamination" of the data by the "direct" magnetic field due to the vertical antenna. Nevertheless, since the actual ground is imperfect, there is still, in general, some "contamination" of this type. To estimate this contamination, the loop was placed on the ground in two locations where there were no ground wires at all, that is, where the loop would simply indicate the vertical H field. Fig. 18 shows the relative amplitude and phase of this H field as a function of distance from the vertical. The power level was the same as that for the measurements at 27.12MHz on the 7 foot long ground wires and so could be regarded as a correction that might be applied to the data on current amplitudes. The source of this field is puzzling; the indicated voltages may

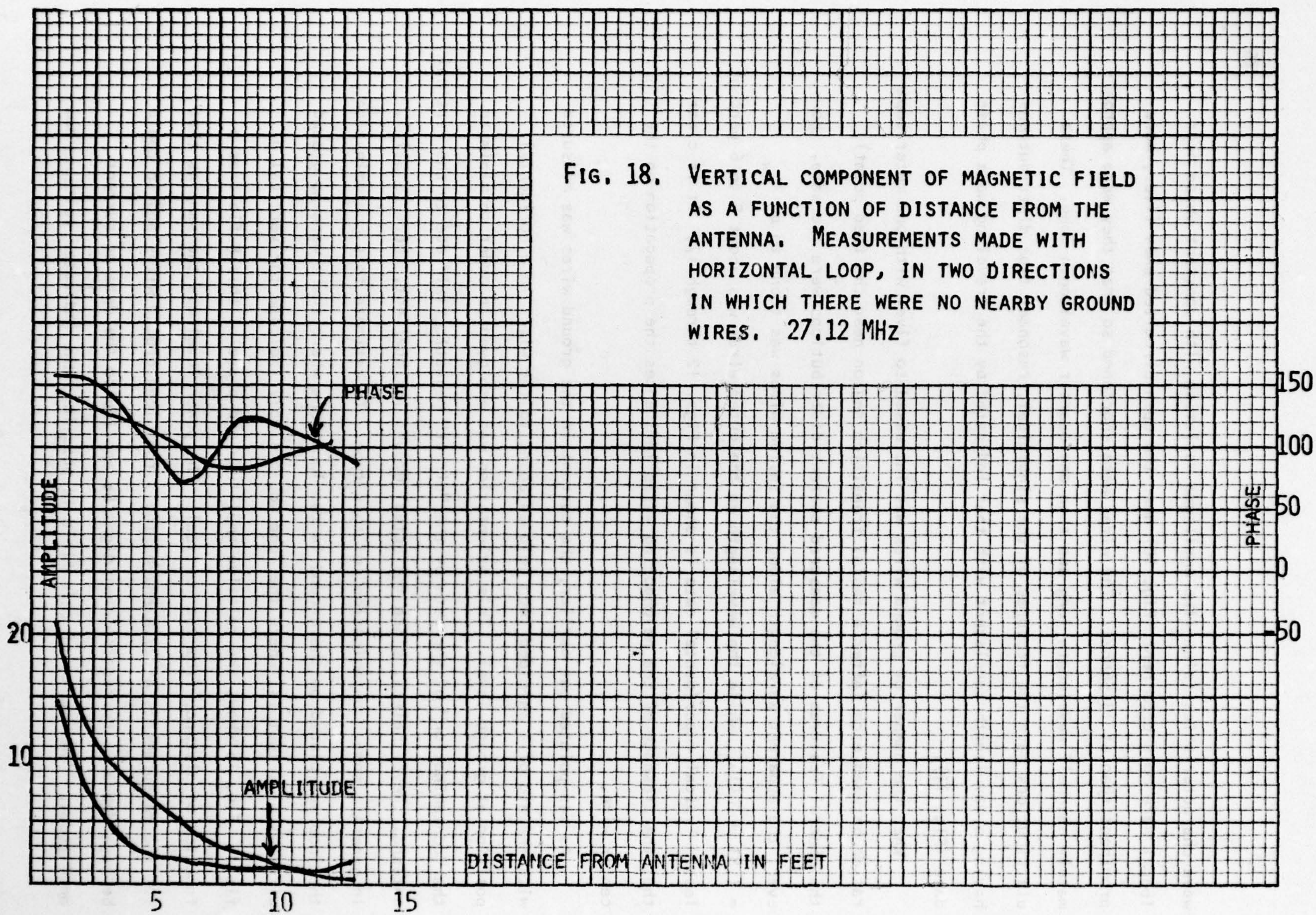


Fig. 18. Vertical component of magnetic field as a function of distance from the antenna. Measurements made with horizontal loop, in two directions in which there were no nearby ground wires. 27.12 MHz

have resulted from stray pickup of other field components.

The measurements at both frequencies were repeated with vertical antennas arranged in a two element array, spaced a quarter wavelength and fed 90° out of phase so as to give a cardioid pattern in the direction of the ground wires. The absolute amplitude was of course different, but the distributions on the ground wires were not significantly different. A system of three ground wires was used between the bases of the two vertical antennas. A standing wave current distribution was observed in these ground wires, with a wavelength shorter than the free space wavelength.

As a final comment, the phase angle of the currents measured often has no absolute significance, since the value is relative to whatever phase reference is being employed. For the earlier measurements, the phase reference signal was taken at the transmitter. For the later measurements, the phase was relative to the signal in a shielded loop attached to the base of the vertical antennas. Also, although an attempt was made to hold it constant, the power output was not constant from day to day, so the amplitude readings should be regarded as only relative values.

4. Measurement of Impedance, Field Strength and Other Characteristics

Except for the case of the $\lambda/2$ monopole at 27.12MHz, the VSWR at the transmitter output, which was monitored continuously along with the power level, was never greater than 1.6 and with the ground wires connected, it was generally below 1.3. With no ground wires connected, so that the quarter wave vertical was fed against the two ground stakes, the input impedance was about 63 ohms with a small positive reactance. With either the long ground wires, or the $\lambda/4$ ground wires, the input impedance was approximately 48 ohms with a small positive reactance. With the ground wires approximately half wave resonant, the impedance increased to about $53 + j20$. The data for the input impedance of the array was not consistent, presumably because the transmission lines were not matched and were imperfect.

Because of limitations of time and weather conditions, it was not possible to obtain vertical plane radiation patterns of the antenna structures with and without ground wires. Instead, to verify the effect of the ground wires on the vertical plane field strength, we investigated the change in field strength between an antenna with no ground wires and the same antenna with several ground wires. Because the terrain was not flat, since in fact it sloped upward slightly in the direction of the ground wires, attention was concentrated at one low angle, approximately 84°. Necessarily, some time elapsed between the measurement with ground wires and that with no ground wires and the conditions of the experiment were not completely under our control. The field strength with the ground wires present as compared to the antennas with no ground wire was between 1.5 and 2 db higher. If we adopt an average increase of 1.75 db, this implies a power increase of about 50%. About half of this power increase would be due to increased radiation efficiency and better impedance match; the remainder of the power increase is presumably due to ground screen radiation. If the ground wires increase the power at low angles by a factor of about 1.25, this implies a field strength increase of about 12%. The evidence is then, that the ground wires increased the field strength between about 8 and 15 percent, at 13.56MHz.

Other observations are also of interest. With three ground wires of quarter wave resonant length, it was found that the sum of the three ground wire currents was approximately equal to half of the current at the base of the antenna. However, when those ground wires were half wave resonant length, the sum of the three currents totalled less than one quarter of the current at the antenna base. This suggests that the ground wires of half wave length are presenting a high input impedance at the base and more of the current is flowing into the ground. However, at the loop of the current on the ground wire, the currents were nearly as large as the input currents in the other cases.

Another question of interest is the division of currents between the ground stakes and ground wires. As might be expected, the current division depends upon the number of ground wires (as well as their length as mentioned above). With a single long ground wire, about one sixth of the total ground current seemed to be flowing in the antenna wire. Initially, there was a substantial ground current flowing on the outside of the coaxial feeder from the transmitter. This current was reduced by coiling the cable so as to present a high blocking reactance to currents on the outside of the coaxial feeder. With three long wires, approximately a third of the ground current seemed to be going into the ground wires, while with five long wires, about half or slightly more of the ground current seemed to flow in the ground wires. An attempt was made to measure the current flow into the ground stakes. Because of the complicated nature of the metal supports, this was difficult. Indications were however, that less than half of the total ground current ever passed into the ground stakes. Thus, with small numbers of horizontal wires, some of the current must have been flowing in incidental stray circuits.

5. Results of Computer Calculations

The best, most sensitive check for agreement between calculated and measured values of the current distribution are those data for long ground wires. For the generation of any numerical results from the large computer program WF-LLL2BP, of course the electrical parameters of the earth must be input. And each time these parameters are changed, another complete calculation must be done (unlike changing wire lengths, for example), and this is time consuming. Moreover, it is known that the propagation characteristics of waves on insulated wires varies significantly with small changes in height above ground; yet the program does not converge satisfactorily if the wire is too close to the ground. All of these factors together suggest that it is not feasible to make a large number of these parameter changes in order to find the best agreement between calculated and experimental results.

Obviously, the first calculations that were carried out were done with our best estimates of the electrical parameters of the earth with essentially the smallest practical distance above the earth. Those results are shown in Figs. 19 & 20. The agreement between the calculated and the experimental results were at best only qualitative. The wavelength along the wire is much shorter than the experimental data indicate. Since it was known that in practice the results are sensitive to the small distance of the wire above ground, this distance was increased in steps. If anything, the agreement was less satisfactory and the trends showed that the really rapid variation in the propagation constants would show up at distances closer to the earth than the distance used in the first calculation.

Next, the value of the dielectric constant input to the program was decreased to the lower extreme of the experimental uncertainty, namely $\varepsilon_r = 4$. The results of these calculations, for a single 66-foot ground wire operated at 13.56 MHz is

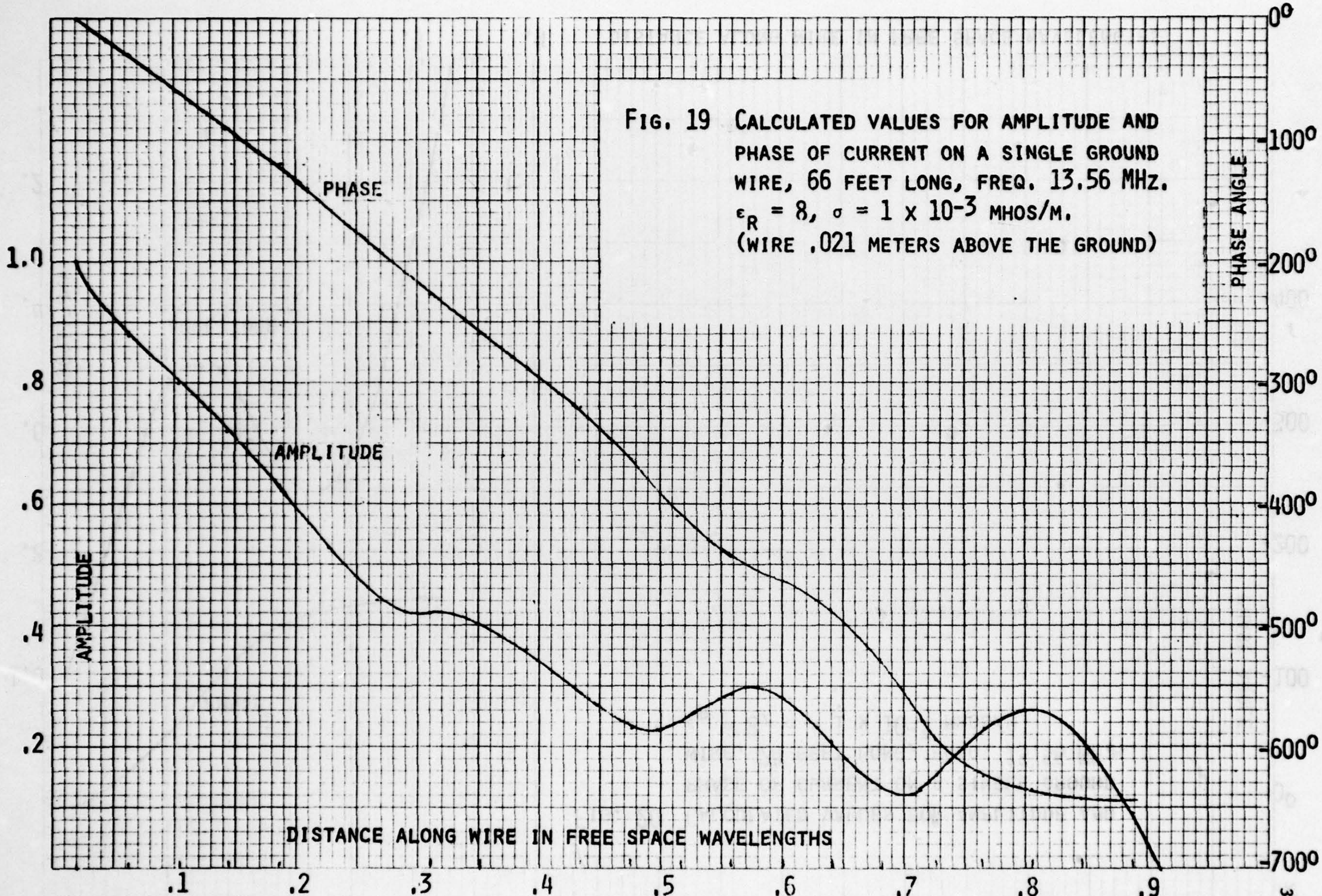


FIG. 19 CALCULATED VALUES FOR AMPLITUDE AND PHASE OF CURRENT ON A SINGLE GROUND WIRE, 66 FEET LONG, FREQ. 13.56 MHz. $\varepsilon_R = 8$, $\sigma = 1 \times 10^{-3}$ MHOS/M. (WIRE .021 METERS ABOVE THE GROUND)

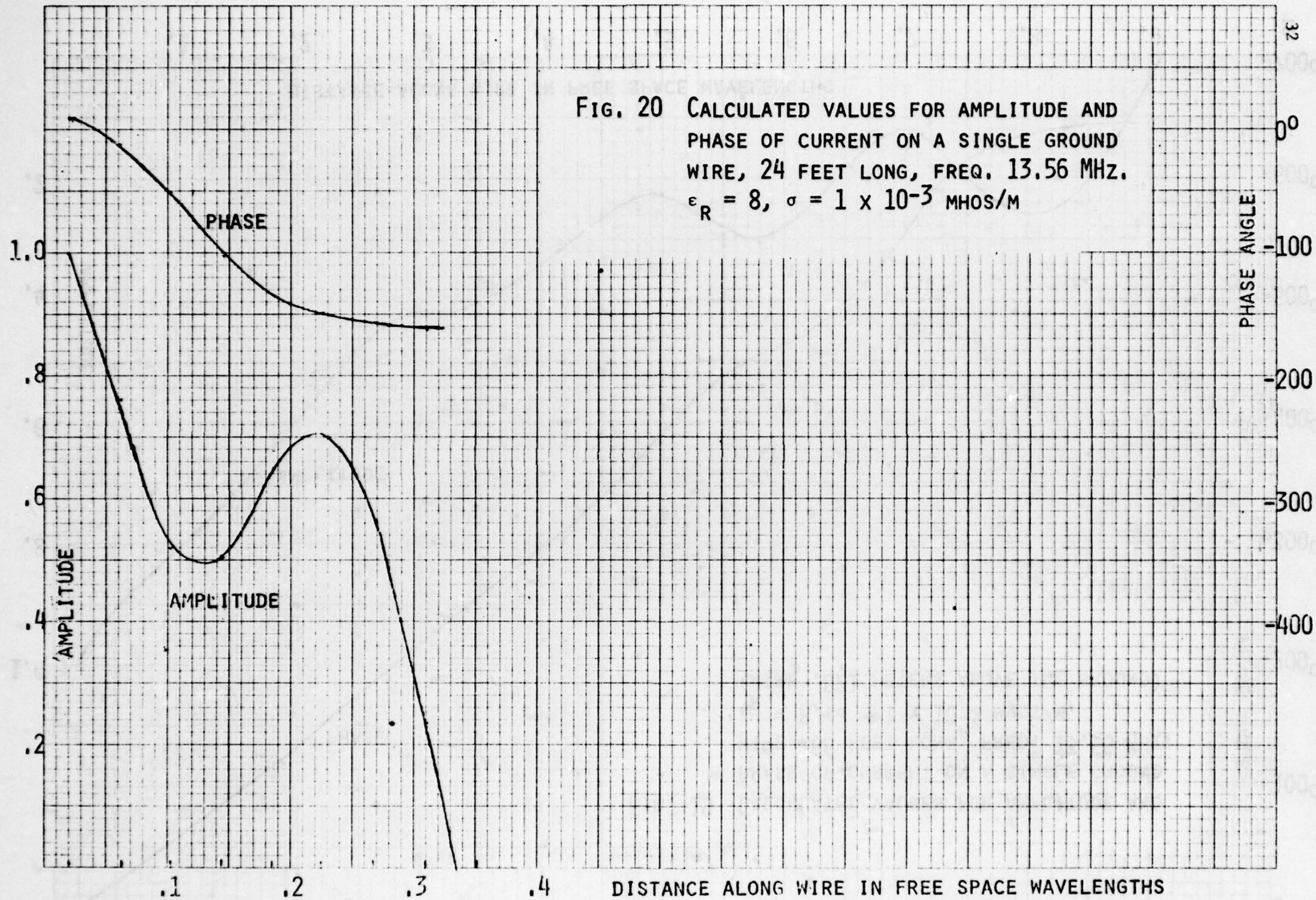


FIG. 20 CALCULATED VALUES FOR AMPLITUDE AND PHASE OF CURRENT ON A SINGLE GROUND WIRE, 24 FEET LONG, FREQ. 13.56 MHz. $\epsilon_R = 8$, $\sigma = 1 \times 10^{-3}$ MHOS/M

shown in Fig. 21. These calculated results should be compared to the experimental data in Fig. 1. The agreement in the phase data (effective phase constant for example) is very close. The amplitude data does not agree as well, but the trends are certainly the same. The discrepancies indicate that the value of conductivity input to the program should have been changed so as to give somewhat more attenuation, since the standing wave pattern near the end of the wire is more pronounced in the calculated data than in the experimental data.

For completeness, the calculations were also carried out with these parameters for a 12-foot, a 24-foot and a 30-foot ground wire. The results are shown in Figs. 22 and 23. These data should be compared to the experimental data given in Figs. 2 and 3. Superposition of the graphical results shows a remarkably close agreement in the phase data. The amplitude trends are also confirmed with the major discrepancy appearing to be a difference attributable to the nominal ground wire lengths used in the experimental data. Since the experimental curves represent many independent trials, it is entirely possible that the nominal lengths given could be a foot or so different from the values shown.

The conclusion seems inescapable. The computer program does indeed predict values that can be measured on actual ground systems. And since the current distributions agree, the radiation pattern calculations, which are straightforward given the current distributions, are also what would be expected in an actual installation. However, for design based on the calculations, the values of the earth parameters must be known, and more precisely than is usual in view of the difficulty of obtaining representative values in practice.

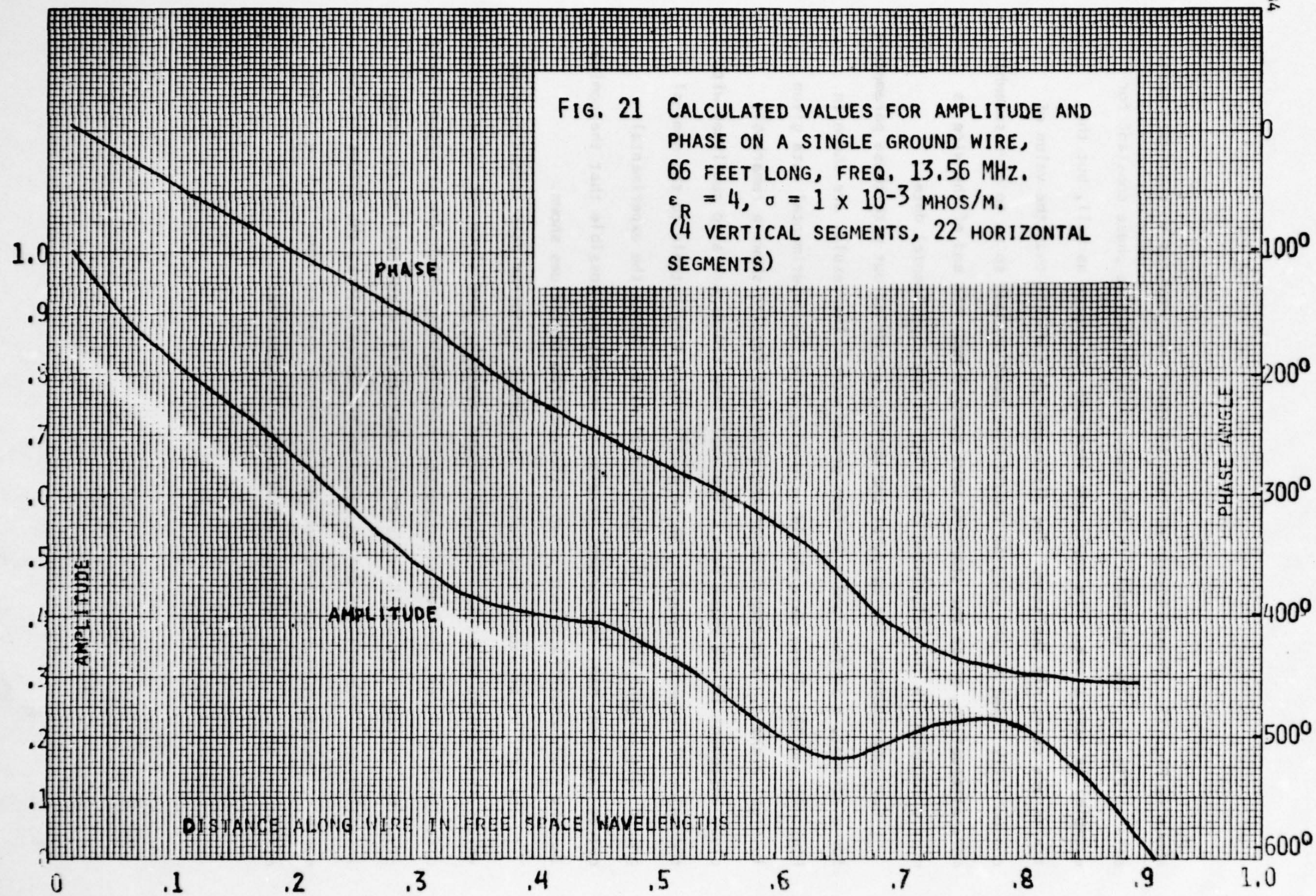


FIG. 21 CALCULATED VALUES FOR AMPLITUDE AND PHASE ON A SINGLE GROUND WIRE, 66 FEET LONG, FREQ. 13.56 MHz. $\varepsilon_R = 4$, $\sigma = 1 \times 10^{-3}$ MHOS/M. (4 VERTICAL SEGMENTS, 22 HORIZONTAL SEGMENTS)

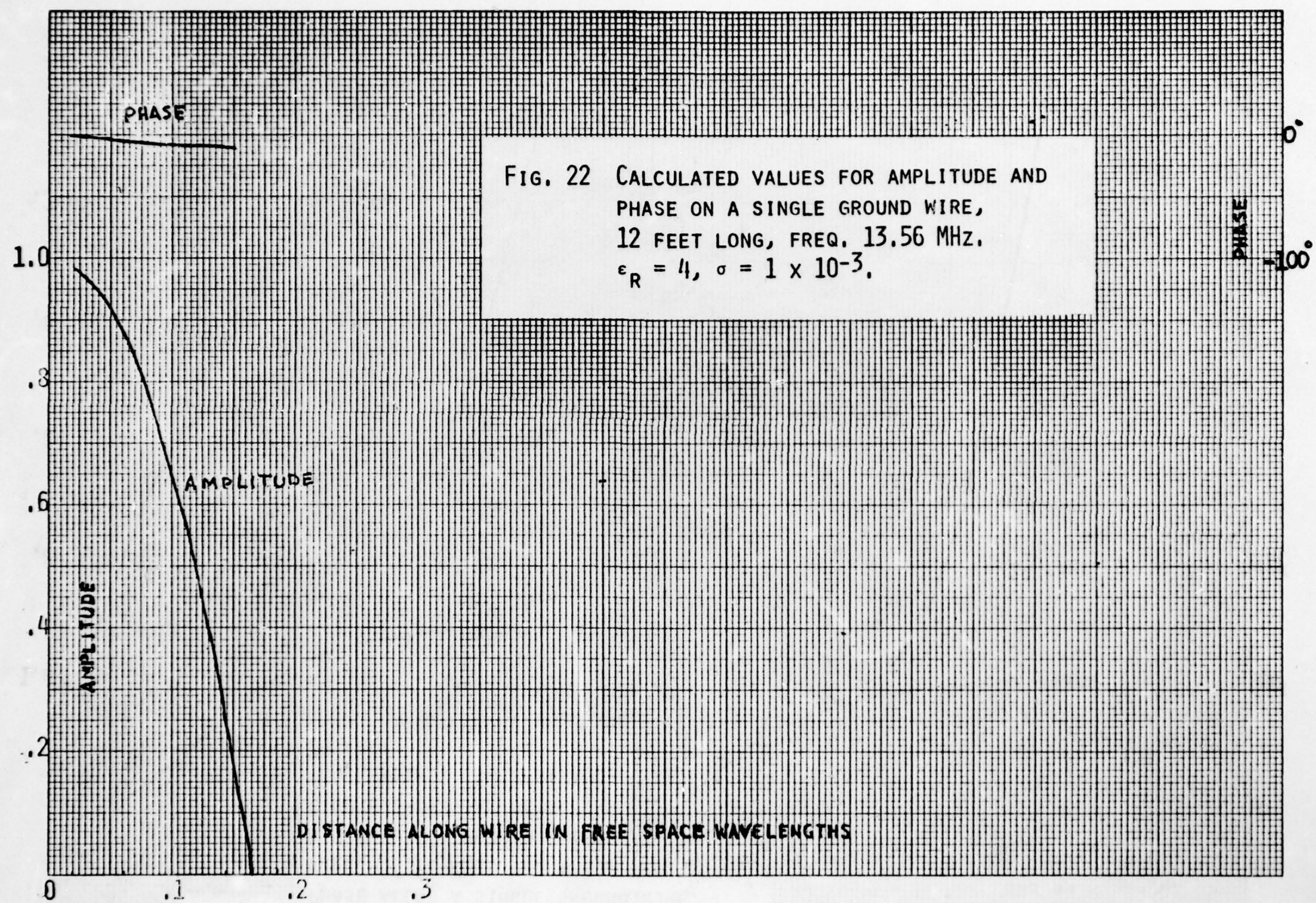


FIG. 22 CALCULATED VALUES FOR AMPLITUDE AND PHASE ON A SINGLE GROUND WIRE, 12 FEET LONG, FREQ. 13.56 MHz. $\epsilon_R = 4$, $\sigma = 1 \times 10^{-3}$.

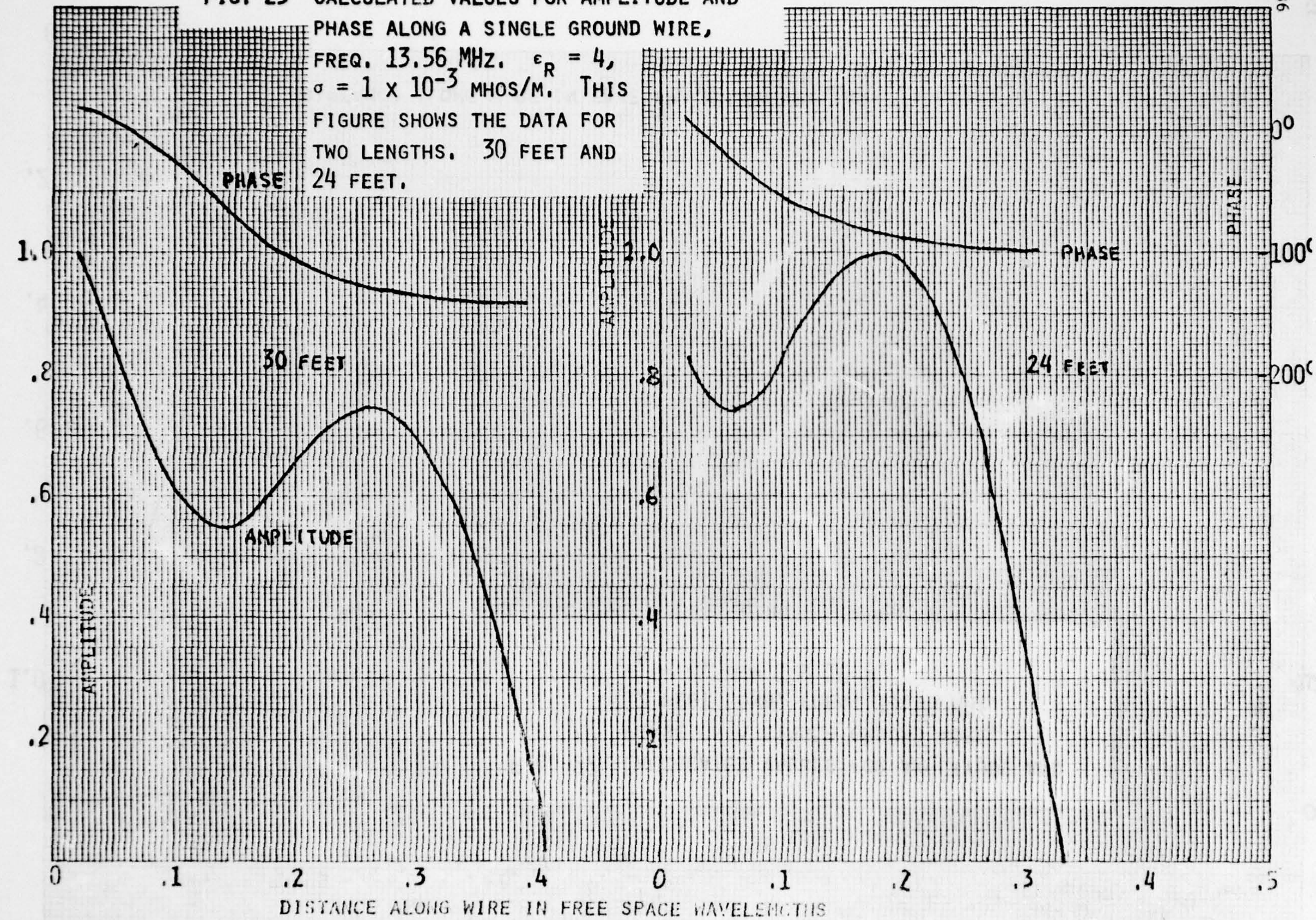


FIG. 23 CALCULATED VALUES FOR AMPLITUDE AND PHASE ALONG A SINGLE GROUND WIRE, FREQ. 13.56 MHz. $\epsilon_R = 4$, $\sigma = 1 \times 10^{-3}$ MHOS/M. THIS FIGURE SHOWS THE DATA FOR TWO LENGTHS. 30 FEET AND 24 FEET.

6. Summary and Conclusions

The theoretical results obtained in a previous contract concerning the current distributions and field effects of horizontal ground wires on HF antenna radiation were found to be, at least qualitatively, in agreement with experimental results obtained in an actual antenna installation. Since the measurements of the electrical parameters of the earth at the antenna site were subject to a large uncertainty, we cannot claim quantitative agreement. While the computer generated results for the phase constant of the currents on the ground wires agree fairly well with Colemans formula, the measured values of phase constant in our installation appear to be considerably higher than would be calculated using our best estimates of the electrical parameters of the earth in Colemans formula; however, the extreme values show satisfactory (remarkable phase) agreement.

The experimental results show an effect which apparently has not been reported previously in the literature. Namely, in a group of parallel ground wires, the phase constant of the currents is not the same in all wires. The center wires of a group have a higher phase constant (more like free space) than do the outer wires, and all wires have a higher phase constant than does a single isolated ground wire on the same ground.

Local and temporary variations in the type of earth cause noticeable variations in the amplitude and phase of the currents in the ground wires. The position of the wire with respect to the ground also has a marked influence.

Relatively small ground wire systems can enhance the field strength of vertical antennas in directions close to the horizon but the effect is not major. To capitalize on this effect, a great deal of information concerning the detailed electrical parameters of the ground all over the transmitting antenna site must be available - much more, in fact, than is normally obtained in practice. Alternatively the current distributions on the ground wires would have to be measured.

Considerable control over the phase constant of the currents in ground wires can be exercised by controlling the spacing of the wires both with respect to the ground and with respect to each other.

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